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## PROGRESS REPORT

Space Life Support Engineering Program

Iowa State University

Ames, Iowa

Period: July 1, 1992 through June 30, 1993

### SUMMARY

This report covers the second twelve months of work performed under a three-year NASA University Grant awarded to Iowa State University to perform research on topics relating to the development of closed-loop long-term life support systems with the initial principal focus on space water management. In the first phase of the program, investigators from chemistry and chemical engineering with demonstrated expertise in systems analysis, thermodynamics, analytical chemistry and instrumentation, performed research and development in two major related areas; the development of low-cost, accurate, and durable sensors for trace chemical and biological species, and the development of unsteady-state simulation packages for use in the development and optimization of control systems for life support systems. In the second year of the program, emphasis was redirected towards concentrating on the development of dynamic simulation techniques and software and on performing a thermodynamic systems analysis, centered on availability or exergy analysis, in an effort to begin optimizing the systems needed for water purification. The third year of the project will be devoted to the completion of the dynamic systems capability, the extension of the thermodynamic analysis to the entire closed loop long term life support system hardware, and the development of a comprehensive model to describe the effect of diet, environment, and exercise patterns on the uptake, redistribution, manufacture, and excretion of water from crew members.



## PERSONNEL

Director: R. C. Seagrave, Distinguished Professor of Chemical Engineering

Post Doctoral Research Fellow: Gadiraju Varma (through May 1, 1993)

Major effort: ASPEN steady-state model development

Graduate Research Assistant: Dasaratha Sridhar (entire period)

Major effort: Fault Detection Algorithm Development

Graduate Research Assistant: Sharmista Chatterjee (entire period)

Major effort: Thermodynamic Analysis, ASPEN Model Development  
of Integrated Physical-Chemical and Biological Systems

Graduate Research Assistant: Susan Doty(entire period)

Major effort: Physiological Water Model Development

Graduate Research Assistant:: Anca Stefanescu (since October 1, 1992)

Major effort: Thermodynamic Analysis and Model Development

Graduate Research Assistant : Megan Scherb(through December 31, 1992)

Major effort: Thermoregulation Model Development

## RESEARCH AND DEVELOPMENT PROGRESS

The present research program is organized in three related, integrated, and highly-coupled projects designed to produce useable results within a three-year period. These projects address some of the unique problems of long-term closed-loop life support systems which are designed for periods of greater than 90 days. Among these are:

- Optimization of life-support systems to operate dynamically over a range of conditions which vary with the diet, exercise protocol, and environmental conditions of the crew



- Optimization of energy consumption and reduction of entropy generation by separation devices, processes, and systems.

- Optimization of process control strategies for conserving energy and material resources while maintaining environmental quality.

Progress during the 1992-93 year has been made in the first two areas, and is summarized as follows.

1. Integration of a working model of the crew into a previously developed system model has been accomplished for the steady state. It is now possible to simulate the behavior of the system at steady state for different crew sizes, of differing physical characteristics and genders, and with different diets. Efforts are continuing during the summer of 1993 to develop a similar material and energy balance model for plants, for incorporation into the overall model. (Results of the crew model are contained in the M. S. thesis of Chatterjee (Appendix 1), while the plant work is being done by an undergraduate summer research student (Tenawati Tanu) who is being co-sponsored by the NASA grant and the Iowa State University Women in Science and Engineering Summer Intern Program.

2. Progress on developing a dynamic model of the crew is occurring in two areas. Susan Doty is developing a dynamic model which will describe the unsteady state distribution of water in the body; that is the uptake, creation, sequestration, and outflow of water in humans as a function of diet, exercise protocol, and environmental factors. Initial development is being done using the dynamic simulation software package EXTEND. Details of this work and some initial results are shown in Appendix 2. The second area of dynamic modeling is the further development of a model of thermoregulatory and fuel depletion aspects of humans-the description of the onset of hyperthermia, hypothermia, dehydration, or glycogen depletion as a function of exercise protocol and environmental parameters. This work, which was performed by Megan Scherb in 1992, is being extended by a summer research student (James Smith) who is also supported by the NASA grant. The results obtained by Scherb are shown in Appendix 3. Both of these efforts will be integrated into the overall ASPEN-based systems model.

3. The importance of availability analysis (exergy analysis) has continued to be a concern as the life support system becomes more complex and as biological interfaces





become more numerous. Our preliminary results in this area are described in a paper by Chatterjee and Seagrave that was presented at the 1993 International Conference on Environmental Sciences in July 1993. A copy is attached as Appendix 4. Present efforts by Anca Stefanescu and Chatterjee are directed towards the development of more rigorous energy and entropy balance equations or unsteady-state, open, complex systems with large numbers of chemical reactions occurring. No such balances are presently available.

## RELATED WORK

During the summer of 1993, Research Assistants Dasaratha Sridhar and Sharmista Chatterjee are engaged in research in the Life Support Division at the NASA Ames Research Center, to gain needed practical experience and to acquire background training for the next stages of the project. Sridhar, whose eventual assignment will be to develop algorithms for fault detection in automatically controlled closed loop systems, is working with Mark Ballin doing high-level programming and model development for the process control problem. Chatterjee is working with John Fisher on super-critical water oxidation, a prime candidate technology for the water regeneration loop in the life support system.

## APPENDIX

1. Chatterjee, Sharmista. M. S. Thesis, Iowa State University. 1993.
2. Doty, Susan. Partial Ph. D. preliminary report on Model Development for Water Regulation in Humans.
3. Scherb, Megan. Development of an Interactive Computer-based Model for determining exercise limitations. Master of Engineering Project, Iowa State University. 1992.
4. Chatterjee, S. and Seagrave, R. C. Paper presented at 1993 ICES meeting.



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## 1 INTRODUCTION

As humans move out from the earth into the Solar system , their most immediate challenge is to provide a life supporting environment in locations that are most devoid of food, air and water. In earlier space flights, life support systems were limited to what may be referred to as open loop configurations. In these configurations, consumables such as water, oxygen and food were stored on board the space craft before the mission. During the mission, these resources were used as necessary and any waste was vented overboard or returned to storage for the duration of the mission. Nothing was recycled.

These open loop ECLSS ( Environmental Control Life Support System ) configurations worked well for short duration missions. But for long duration missions or to establish a permanent station it is imperative to include regenerative systems in order to reduce the weight of expendables supplied through logistic support.

Autonomy from Earth requires the development of a closed loop ECLSS comprised of human, plant and animal modules. The modules must be integrated with a Waste Management System ( WMS ) to achieve partial and ultimately long-term self-sufficiency.

### Goals and Methods of Approach

Our first goal in this project was to perform a systems analysis of a closed loop ECLSS. This pertains to the development of a model of an existing real system from which to assess the state or performance of the existing system. As far as extraterrestrial life support systems are concerned there are no real systems from

which to derive a model. Therefore, systems analysis is applied to conceptual models obtained from a system design effort. This can serve several purposes:

- (1) To quantify approximate reservoir and flux values of the critical components within the system such as oxygen, hydrogen, nitrogen and carbon dioxide.
- (2) To compare technology candidates for a technology trade study.
- (3) To determine the sensitivity of the system to uncertainty in system variables.
- (4) To serve as a basis for future dynamic modelling of the system.

For our modelling purposes we used a simulator tool called ASPEN ( Advanced System For Process Engineering) . The reasons for choosing ASPEN will be elucidated later on in this thesis.

Our second goal was to evaluate the thermodynamic efficiency of the different components comprising an ECLSS. Use is made of the second law of thermodynamics to determine the amount of irreversibility or exergy loss of each component. This will aid design scientists in selecting the components generating the least entropy, as our penultimate goal is to keep the entropy generation of the whole system at a minimum.

## 2 DISCUSSION OF BACKGROUND MATERIAL

### Overview of Life Support System

Under the new space exploration initiative adopted by NASA a permanently manned orbiting platform called Space Station Freedom (SSF) is to be constructed. The most immediate challenge facing scientists is to provide a life supporting environment on the SSF. The open-loop life support systems currently in use by the United States require that the air, food and water needed by humans in space be supplied from the Earth. These same systems are unable to recycle the waste products that result and these must be returned to the Earth or left in space. Since humans require approximately 6.5 kg of potable water, air and food each day, provisions for a crew of four run to nearly 9500 kg per year. In addition, if the crew is to bathe, wash dishes, flush toilets and clean clothes, then the crews needs swells to nearly 28,500 kg of provisions each year, (Rummel,1990). This is the overboard on space operations. As long as mass to orbit is a quantity to be conserved, then recycling of life support commodities represents one of the best ways to lower this overhead.

The objective of a regenerative ECLSS is to recycle the resources required for the mission. This increases the self-sufficiency of the system and creates what is commonly termed as the Closed Loop Environmental Control Life Support System.

The usefulness of the closed loop system is further corroborated by loop closure studies,(Humphries et al., 1986). They considered the on-orbit and resupply weight and volume of a series of impacts ranging from a completely open loop to a closed

loop water and oxygen recovery system. As illustrated in Figure 1, there is a considerable reduction in cost for a closed loop system

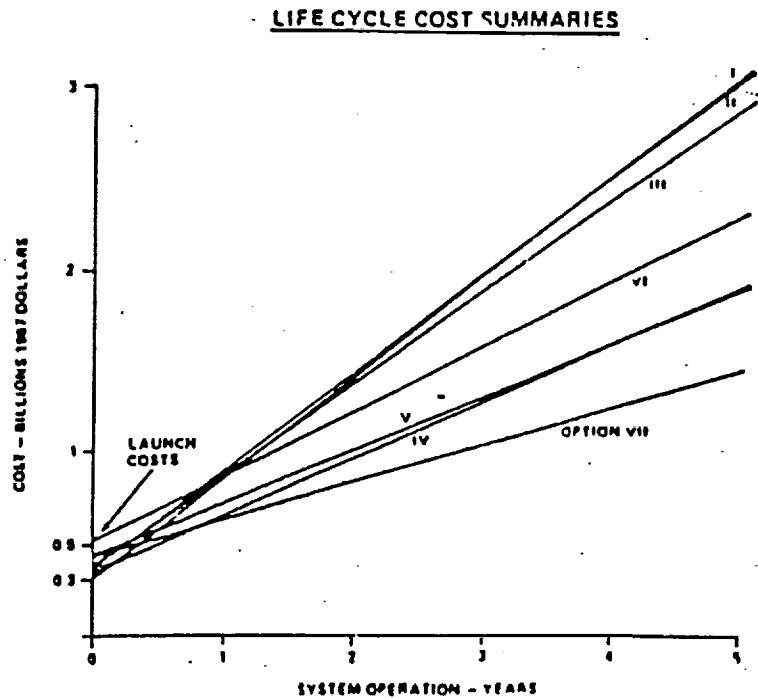


Figure 1: Loop closure cost summaries

where

- OPTION 1 is a completely open system using oxygen resupply, LiOH carbon dioxide removal and water resupply.
- OPTION 2 replaces the LiOH system with regenerable carbon dioxide removal.
- OPTION 3 added an oxygen generation system and processed the condensate water for reuse in the oxygen generator. Excess hydrogen was compressed and returned to the Earth.

- OPTION 4    added hygiene water recovery.
- OPTION 5    added urine reclamation to OPTION 4.
- OPTION 6    added different types of carbon dioxide reduction.
- OPTION 7    combines closed loop oxygen and water recovery systems, adding urine reclamation and potable water recovery to OPTION 6.

### Subsystems of the ECLSS

The closed loop life support system can be primarily subdivided into seven subsystems, (Gustavino and Mankamy, 1989). They are :

- (1) THC (Temperature and Humidity Control)
- (2) ACS (Atmosphere Control and Supply)
- (3) AR (Air Revitalization)
- (4) FDS (Fire Detection Subsystem)
- (5) WRM (Water Recovery and Management)
- (6) WM (Waste Management)
- (7) ES (Extra vehicular activity Support)

The functions of the above subsystems are defined in Figure 2.

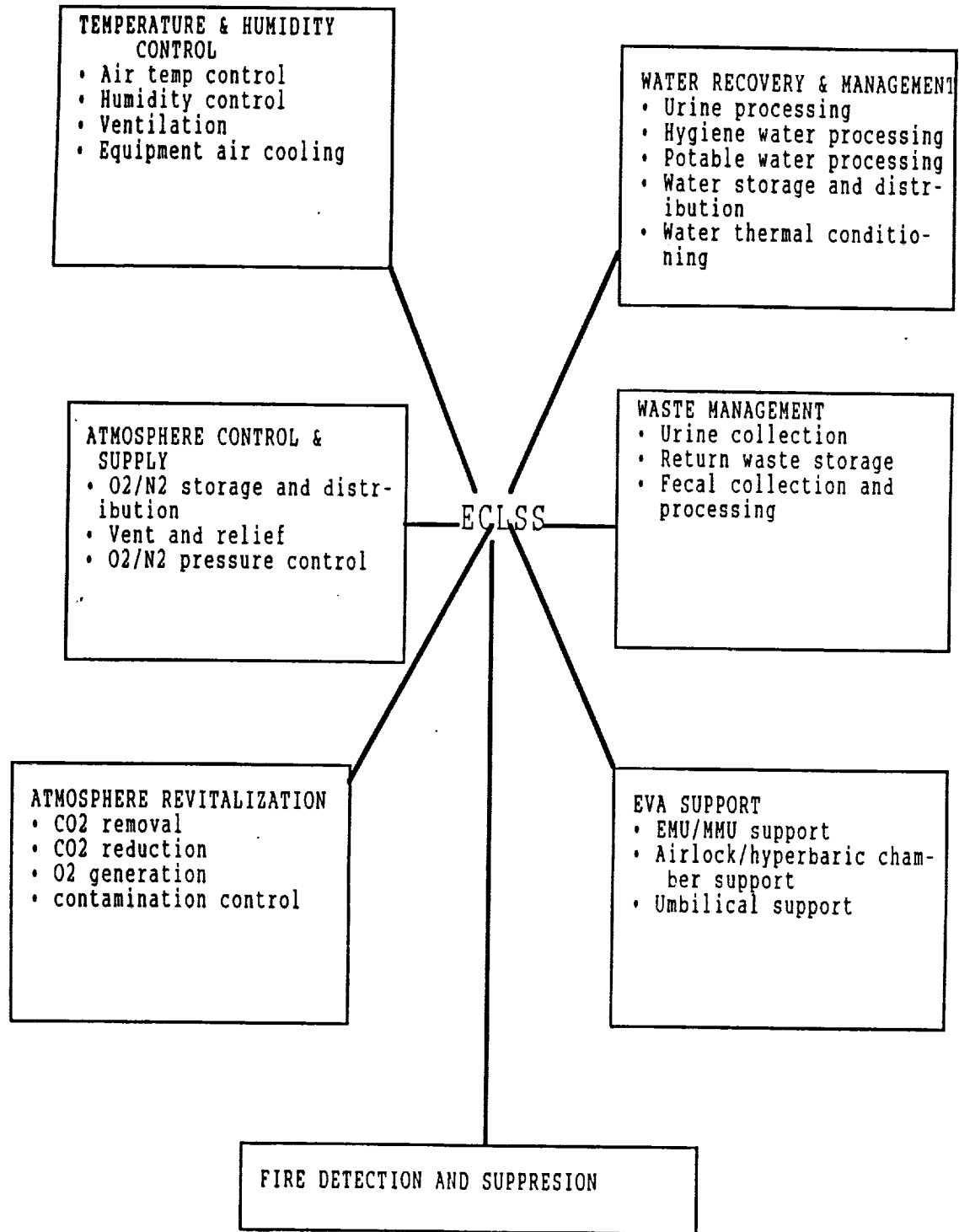


Figure 2: Functional units of the ECLSS (Adapted from Humphries, et al., 1986)



### Types of Life Support Systems

There are two types of Life Support Systems :

- Physico-Chemical type
- Bioregenerative type

The **Physico-Chemical** type of Life Support is an example of a medium term regenerative design. In this approach the different subsystems of the ECLSS uses physico-chemical methods to recover metabolic oxygen from respiratory carbon dioxide and fresh water from contaminated water. Food and waste are treated as open loop consumables and expendables. However, the supply of food will also constitute a source of water. The primary source of energy is electrical energy.

The **Bioregenerative** type will provide partial closure of the food loop with food production and partial waste recovery of the plant material (Gustavino and Mankameyer, 1989). The Bioregenerative approach is commonly referred to as the Controlled Ecological Life Support System (CELSS). A CELSS uses plants to imitate the same process that support life on Earth , with one important difference. On Earth there are large buffers to keep the balance between the various elements, but in space these buffers will be minimal. Hence it is very essential to maintain a high degree of control over the process involved. In this system the carbon dioxide which is generated is used by the plants which separate and release oxygen. The carbon is then used along with water and light energy to produce food. After the crop is harvested, the inedible parts of the harvest are used as fertilizers so the portion of the nutrients generated by the plants may be recovered. The primary energy supplier for this design is the sun. Interaction between the different components of CELSS is shown in Figure 3.

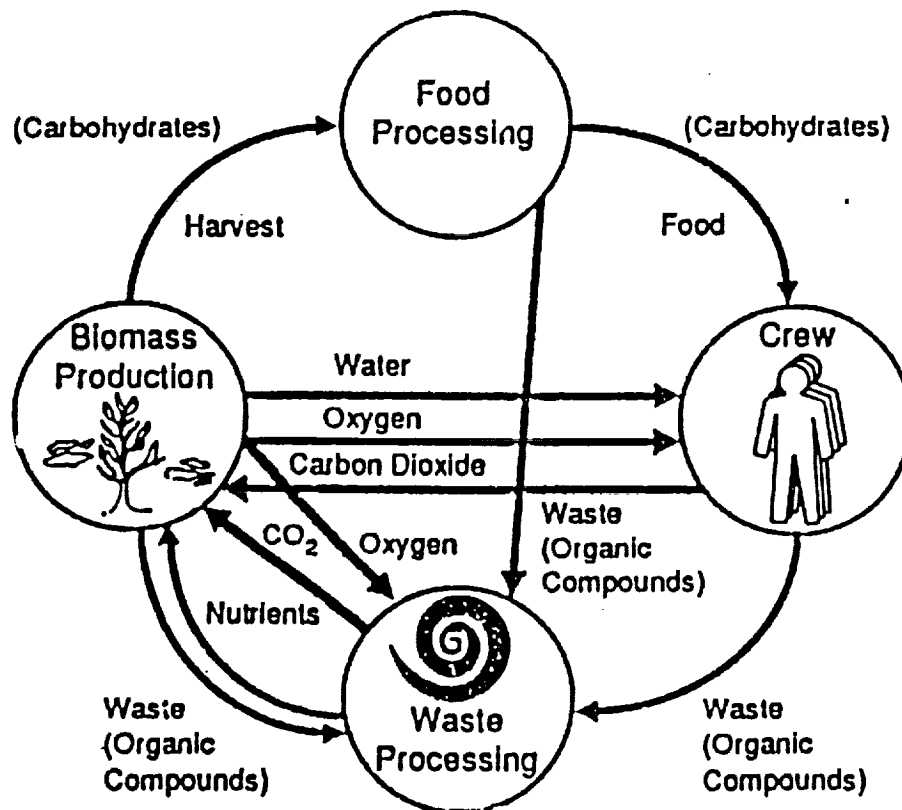


Figure 3 : Various Components of a Bioregenerative Life Support System  
(Adapted from Gustavino and Mankameyer, 1989)

### Need For Computer Modeling

In order to achieve reliable and economical life support during the various extra-terrestrial missions, critical and difficult choices have to be made:

- At the system level, such as between storing and regenerating essential supplies.
- At the subsystem level, such as between physico-chemical and bioprocessing for regeneration of oxygen;

- At the compartment level such as between the Bosch or Sabatier process for reduction of carbon dioxide.

Computer modeling can be used to evaluate proposed system designs with respect to the above mentioned criteria without carrying out extensive laboratory experiments. Thus, time and money required for technology testing can be reduced.

Computer modeling is also an effective way to check component design specifications and to identify subsystem interface problems. It allows for the examination of critical operating conditions, performance of failure mode analysis and determination of total system performance. This enables the engineer to determine which designs require further development.

### Discussion of ECLSS Simulation techniques

In view of the ongoing developments, the applications of an ECLSS simulation tool can be broadly categorised into two divisions, (Simon et al., 1991). These are :

- Mission Analysis
- Assessment of Operational phases.

A major point of interest during mission analysis lies in the budgeting of consumables and disposables such as water and oxygen. For this purpose it is sufficient to determine steady state solutions for most phases of the mission. For the assessment of operational phases such as the launch, transient modeling of the system is used. Transient modeling is also used in failure mode analysis.

In the area of steady state modeling notable work has been done at the Jet Propulsion Laboratory, California, (Seshan et al., 1991) , in developing a Generic Modular Flow Schematic ( GMFS ) architecture capable of encompassing all functional elements of a physical/chemical life support system. The GMFS is coded in ASPEN. It can be used to compute the material, heat and power flow quantities of every stream in each of the subsystem functional elements for the chosen ECLSS configuration. The input requirements for the GMFS are crew requirements and power data which are obtained from previous bread-board test results. The comprehensive ASPEN material and energy balance output is transferred to a systems and technology assessment spreadsheet for rigorous system analysis and trade studies.

In the field of transient modeling the software to be used by NASA in the 1970's and early 1980's was General Environmental / Thermal and Life Support program ( G189A ), (Barker et al., 1971). G189A is a complex program written in FORTRAN-5 and FORTRAN-77. It is modularized using numerous subroutines. G189A has a

number of advantages. It offers the advantage of steady-state, quasi-transient or true transient logic. It also has the flexibility of preprocessor and post processor subroutines. However the major limitations of G189A is that it has limited physical property and stream data structures which cannot take into account the different components present in a normal ECLSS. Moreover, advanced technologies can introduce new operations in life support systems which are not modeled by G189A.

In the later half of the 1980's a Computer Aided Systems Engineering and Analysis ( CASE/A) ECLSS series was designed as a general ECLSS design and analysis package, (Bangham and Reuter, 1987). This program evolved from both the G189A and SINDA programs and shares the G189A architectural concepts. The designer/analysis interface is graphics based and allows the designer to build a model by constructing a schematic of the system under consideration. CASE/A provides for transient tracking of the flow stream constituents and determination of their state ( e.g temperature, pressure, composition) throughout the ECLSS. However the limitations of G189A are also present in CASE/A.

In the European space arena in 1989 a new software was developed called ECOSIM, which is capable of simulating ECLS subsystems, (Perez and Torroglosa, 1991). ECOSIM provides a graphical language. It is based on a set of icons, each representing a specific ECLSS component the user can select to build a complete system schematic. The ECOSIM simulation is based on a mathematical model of the ECLS system under consideration, its environment and the scenario applied. The basic formalism accepted by ECOSIM is a non-linear, state-space continuous time model subject to discrete events. The solution of the mathematical model is then accomplished using a standard implicit differential algebraic equation solver.

### Development of an Integrated Steady State model of a Closed Loop Environmental and Life Support System

Our first goal in this work has been to develop a closed loop steady state physico-chemical process model. The distinctive feature of our model which is not present in any earlier work, (Seshan et al., 1991) is that the input requirements for the various ECLSS subsystems is determined from the user written 'crew' model. A Fortran block is appended to the main program to simulate the basic metabolic operations of the crew. The system is completely closed with respect to free water and oxygen, the only inputs being food which includes dry food (i.e carbohydrates, fat and protein) and water present in food. The utility of the crew model and its salient features will be dwelt upon in the following chapter.

Another feature of our approach is a reservoir concept which was adopted throughout the model to improve its versatility. The outlet flows of some subsystems are not directly connected to the inlet of another, but rather are connected to a reservoir. In addition to reducing the modeling effort, this allows for resource sharing among subsystems and would help in sensitivity analysis of the system.

The model is coded in ASPEN (Advanced System for Process Engineering). ASPEN is an application program developed for steady state, chemical process simulation, (ASPEN PLUS USERS GUIDE, 1988). The program allows the user to model a process flow-sheet by sequencing chemical operations similar to an actual process. The program provides basic 'block' operations, such as pumps, mixers, heat exchangers, compressors and other widely used unit operation blocks that an user can put together to represent a chemical process. Over 1000 chemical species, including gases, liquids and solids are available to the user with physical and

chemical property data included. The program also permits the inclusion of user-written FORTRAN subroutines for custom operational blocks. As mentioned earlier, there are other ECLSS simulators available such as G189A and CASE/A. However, in a study by the NASA Ames Research center to evaluate the existing software for life support modelling (Likens and Force, 1988), ASPEN was rated the highest. Hence ASPEN was chosen for our model. The details of ASPEN modelling of the various ECLSS subsystems will be elucidated in chapter 4.

Of the seven ECLSS subsystems mentioned earlier, our model does not take into account the FDS and the ES. The interactions between the other subsystems with the crew is illustrated in Figure 4.

Figure 4: Relationship between the Crew and the Life Support Subsystems



### 3 HUMAN HABITAT MODULE

The principal components of the human habitat module are

- Crew
- Cabin where the crew is residing

We shall now elucidate the strategies adopted in modeling the crew and the crew living space.

#### THE CREW MODEL

##### Need For Development of the Crew model

Long range goals for the space program include the establishment of a man - tended lunar base and human expedition to Mars as a stepping stone towards expansion of humanity into space (National Commission on Space,1988, and NASA TM ,1988). The requirements of the human module 'drives ' the design and operation of an ' ECLSS '. The outputs from the crew model determine the mass flow rates of the different flow streams into the other subsystems of the ECLSS. The objective here has been to develop a computer model to simulate the metabolic inputs and outputs from the crew module, accounting for the human body mass, age and gender and various categories of physical activities. Metabolic inputs to the human module consists of oxygen, food and water while the metabolic outputs include carbon dioxide, solid feces, urine and insensible water ( perspiration and respiration ).

### Model Development

The crew module primarily consists of two subsystems : inputs and outputs. In developing this model the following assumptions were made:

- With the functional dependence of energy activity upon gravity not being clearly understood due to lack of available experimental data it was assumed that the basic relationships which are obtained for terrestrial data hold under reduced gravity conditions. It is however expected that energy expenditure rate in fractional gravity (e.g Lunar 1/6 g or Martian 1/3g) is smaller than at 1g for a given activity (Sadeh, 1989).
- The crew is at steady state so there is no accumulation of food or water by any individual, i.e the weight of the individual remains the same.

The premise of this study is then that all of the input/output streams to the crew module are determined by the energy expenditure rate .

The crew module is now determined based on the following considerations:

- Determination of basal metabolic rate.
- Energy activity
- Metabolic input requirements
- Metabolic wastes.

### Basal Metabolic Rate

Basal metabolic rate or basal energy expenditure is defined as the heat expended by an individual at least 10 hours after the last meal, resting in a lying position, awake, at a normal body and ambient temperature and without any physical or physiological stress. The basal metabolic rate is expressed in Kcal per day per square meter of body surface.

The basal metabolic rate is a function of age, body mass and gender. It is evident that there is a non - negligible influence of age on energy expenditure, (Fleisch 1951). Also, it is known that the magnitude of energy expenditure is a function of the amount of active cells in the body or body cell mass. Women have more adipose tissue and less muscle than men, and therefore have a lower metabolic rate than men.

Hence the following equations as suggested by Dreyer in 1920 , can be used to compute the basal metabolic energy of men and women from the age of 5 onwards, (Sherman, 1952)

$$\text{Male : BEE} = \frac{W^{0.5}}{0.1015 \times A^{0.1333}} \quad (1)$$

$$\text{Female : BEE} = \frac{W^{0.5}}{0.1127 \times A^{0.1333}} \quad (2)$$

where BEE : Basal metabolic rate / Basal energy expenditure in Kcal  
per 24 hours

W : weight in grams

A : age in years

### Energy Activity

The crew members of Space Station Freedom will be engaged in a wide variety of on base " shirt-sleeve " earthlike activities. It is assumed that the crew will be engaged in four basic human physical activities :

- (1) Rest/Lying
- (2) Walking
- (3) Sitting

#### (4) Running

According to our assumption that terrestrial relationships hold good in the space station, we can use the following relationships to express the different human activities in terms of the basal metabolic rate, (Lusk,1928).

ACTIVITY	ENERGY EXPENDITURE
Lying	BEE
Walking	2.57BEE
Sitting	1.23BEE
Running	7.86BEE

where BEE : basal energy expenditure in Kcal/hr

Figure 5 depicts the influence of the energy activity on the crew.

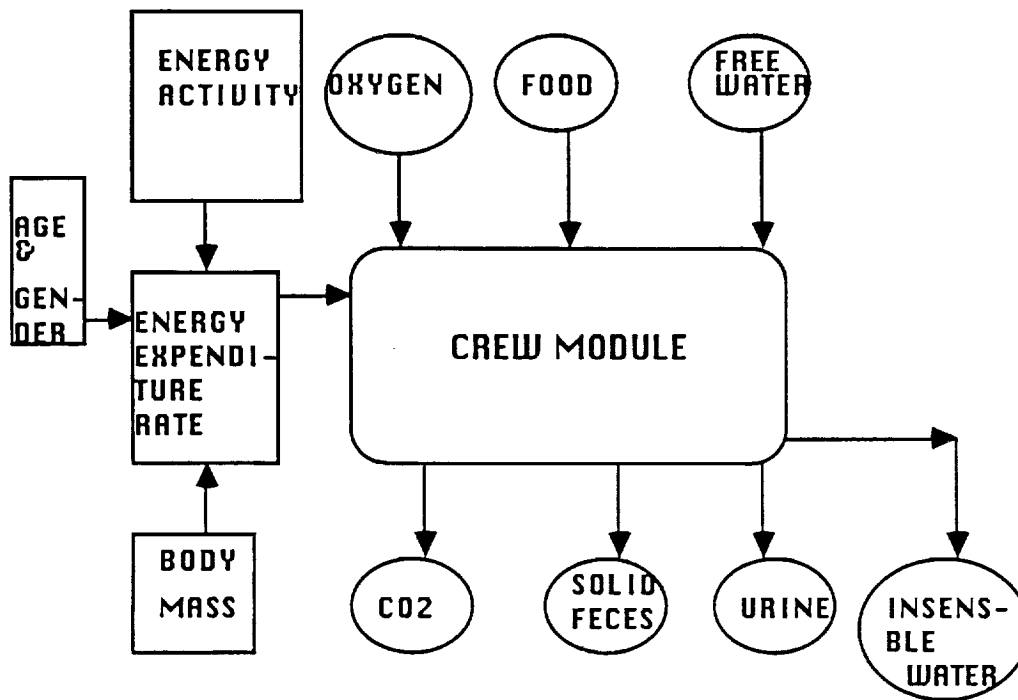


Figure 5: Metabolic mass flow rates for the human module (Adapted from Sadeh et al., 1989)

#### Metabolic Input Requirements

Metabolic inputs for the human module consists of food (dry food together with water in food), oxygen and water as shown in Figure 5 above. The mass flow rates of these metabolic inputs was expressed in terms of the energy expenditure by the crew in one hour.

#### Dry Food Consumption

Dry food is the main source of energy to the body and consists of macro and micro nutrients and vitamins. The major components of dry food are the macro nutrients which are composed of carbohydrates, proteins and fats. Consequently, for our modelling study here we only have to take the major macro nutrients into consideration.

The normal diet of a person consists is taken as 200g of carbohydrates, 70g of protein and 60g of fat, (Lehninger, 1977). Using the same composition as prescribed by Lehninger for the crew, we can express the mass fraction of protein and fat in the diet in terms of carbohydrate present as

$$P = 0.35 \times C \quad (3)$$

$$F = 0.30 \times C \quad (4)$$

where

P = amount of protein in diet in grams

F = amount of fat in diet in grams

C = amount of carbohydrate in diet in grams

For our calculation the representative compounds used as typical carbohydrate, fat and protein were Glucose ( $C_6H_{12}O_6$ ), Palmitic Acid ( $CH_3 [CH_2]_{14} COOH$ ) and Alanine ( $NH_2CH [CH] COOH$ ) respectively, (Stokes,1988).

All the energy required by man is obtained from food. The energy produced through metabolism of one gram of carbohydrate, fat or protein is 4.17, 9.3 or 4.3 Kcal respectively (Bursztein et al., 1989)

Knowing the energy expenditure of a crew member (man/woman) in one hour, the amount of food required is thus computed as

$$TEE = 4.17 \times C + 9.3 \times F + 4.3 \times P \quad (5)$$

where

TEE - Total energy expenditure

From (3) and (4) the amount of fat and protein can be expressed in terms of equivalent carbohydrates. Thereby, the total carbohydrate required for metabolism is

$$C = \frac{TEE}{(4.17 + 9.3 \times 0.3 + 4.3 \times 0.35)} \quad (6)$$

However, it is known that when food is eaten, not all of it is absorbed, some passes through the intestine and is excreted in feces. From literature it is known that approximately only 93 % of protein and 98 % of fat are metabolized, (Merrill and Watt, 1955, Southgate and Durnin, 1970). On this basis the actual amount of carbohydrate, fat and protein to be supplied in diet can be computed. Thus the total dry food requirement ( TDF ) is given by

$$\text{TDF} = \frac{C}{0.98} + \frac{F}{0.98} + \frac{P}{0.93} \quad (7)$$

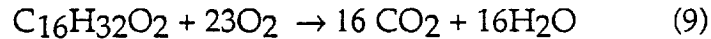
### Oxygen Requirement

Oxygen is required for the metabolism of carbohydrates, fat and protein. Stoichiometric relations for the metabolism of the three macro - nutrients is given below :

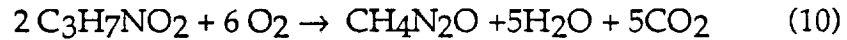
Carbohydrate



Fat



Protein



From the above relations (8), (9) and (10) we can deduce that for metabolizing 1gram each of carbohydrate, fat and protein we require 0.85, 2.29 and 0.86 liters of oxygen respectively at body temperature and pressure. Thereby

$$\text{VO}_2 = 0.85 \times C + 0.86 \times P + 2.29 \times F \quad (11)$$

where

$\text{VO}_2$  is the amount of  $\text{O}_2$  consumed in liter per hour

### Water Requirement

The total water input to the crew consists of metabolic water  $H_2O_M$  ( i.e water produced through the metabolism of food ), water in food and free/drinking water. Apart from this the crew also requires water for their daily activities like shower, laundry etc. This is termed as hygiene water.

Metabolic water is produced through the physical and chemical processes involved in the metabolism of dry food. The metabolic water mass flow rate is proportional to the consumption of macronutrients as shown by the stoichiometric relation below. This was derived on the basis of reactions (8), (9) and (10).

$$H_2O_M = 0.6 \times C + 0.51 \times F + 1.125 \times F \quad (12)$$

The amount of water associated with dry food is 1.32 lb per lb of dry food, (Hall, 1990). Knowing the amount of dry food consumed we can thus evaluate the amount of water entering through food.

Water required for drinking is calculated by performing a water balance over man. Since the man is assumed to be at steady state there is no overall accumulation of water in man. As shown in Figure 5, the output water streams from the crew are urine and insensible water. The mass flow rates of these output water streams is determined as a function of energy expenditure. Hence, water required for drinking is the difference between the total water output and the summation of water input in the form of metabolic water and food water.



### Metabolic Wastes

In a closed loop ECLSS the metabolic wastes from the crew are treated, recycled and managed for utilitarian use. Metabolic waste outputs from the crew consists of carbon dioxide, solid feces, urine and insensible water (this includes perspiration and respiration water) as shown in Figure 5. In addition the crew also generates a wide variety of non metabolic wastes such as hygiene water, food packaging wastes and manufacturing wastes. In our model only hygiene water is taken into consideration in this category.

### Carbon dioxide

As shown in reactions (8), (9) and (10) carbon dioxide is produced during the metabolism of macro nutrients. Thereby, from the above mentioned relations it is computed that on metabolism 1g of carbohydrate, fat and protein each produces 0.85, 1.59 and 0.71 liters of carbon dioxide respectively at body temperature and pressure.

$$VCO_2 = 0.85 \times C + 0.71 \times P + 1.59 \times F \quad (13)$$

where  $VCO_2$  is the amount of  $CO_2$  produced in liters in hours.

### Feces Production

Here we are only taking into account the solid feces production. An input /output mass balance implies, to a first approximation, that the feces production is equal to the dry food inputs less the amount of food metabolized by the body. Going by the above analogy the total amount of solid feces is

$$SOLID FECES = TOTAL FOOD - METABOLIZED FOOD$$

$$\text{SOLID FECES} = \left( \frac{\text{INTAKE C}}{0.98} + \frac{\text{F}}{0.98} + \frac{\text{P}}{0.93} \right) - (\text{C} + \text{F} + \text{P}) \quad (14)$$

### Urine Production

Urine is composed of liquid and solid particulates and daily average values of the various constituents of urine as obtained from (NASA database,1992) is shown in Table 1.

Table 1 : Composition of Urine Analog (Adapted from NASA database)

Substance	Amount (person/day)	Su
		Wa
Water	1454 ml	
Urea	21.0045 g	
Chloride	8.836 g	
Sodium	4.9376 g	
Potassium	3.80746 g	
Sulfate ion	3.251 g	
Creatinine	2.3572 g	
Hippuric acid	1.77958	
Citric acid	0.995362 g	
Glucuronic acid	0.949905 g	
Ammonia	0.849585 g	
Uric acid	0.73359 g	
Tyrosine	0.681862 g	

The principal constituent of urine is urea, which is formed during protein metabolism as shown in (10). Thus the amount of urea present in urine is

$$WRU = 0.332 \times P \quad (15)$$

where  $WRU$  is the urea produced in grams

We make an assumption here that the urine urea concentration of the crew remains constant irrespective of the crew exercise level. From Table1, the amount of water to be associated with the urea to obtain the desired urine concentration is

$$W_{IU} = W_{RU} \times \frac{1454}{21.0045} \quad (16)$$

where  $W_{IU}$  is amount of water in urine in ml.

### Insensible Water Production

Insensible water is produced by perspiration and respiration from the crew members.

When the crew members are at a resting neutral steady state the body core temperature of an individual remains constant at 98.6 °F. When the crew is engaged in activities which expend energy in excess of basal metabolic activity, the sweat production increases in order to keep the body core temperature at the desired value by removing more heat from the body surface by evaporation of sweat. This is illustrated in Figure 6, which shows sweat production in gm per hour as a function of energy metabolism, (Stegemann, 1977). It is observed that there is a disproportional rise in sweat production in relation to the increase in energy metabolism

From Figure 6 linear relationships between energy metabolism and sweat production were derived. When energy metabolism is less than or equal to 250 Kcal/hour ,

$$SW = 1.50 \times (\text{energy metabolism}) - 75 \quad (17)$$

For energy metabolism greater than 250 Kcal/hour

$$SW = 2.50 \times (\text{energy metabolism}) - 325 \quad (18)$$

where  $SW$  is the amount of sweat produced in grams

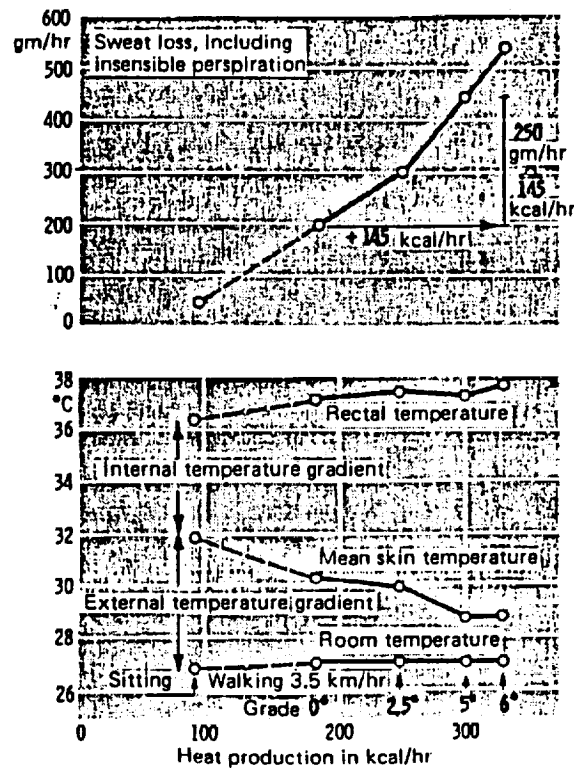


Figure 6 : Sweat loss in man at different levels of heat production.( Adapted from Stegeman, 1977)

Water lost by respiration is equivalent to the amount lost in saturating the inspired air. The partial pressure of water vapor in inspired and expired air is 15 and 47 mm Hg respectively, (Seagrave, 1971). Thereby total volume lost as respiration is the difference in volume of water in expired and inspired air. Procedure to calculate the total volume of inspired and expired air will be dealt with in the next section.

## CABIN MODEL

The cabin model is used to maintain the requisite environmental criterion in the cabin at 20.8% oxygen, 76.9% nitrogen, 0.3% carbon dioxide and 73.7% relative humidity at 70 ° F (Humphries et al., 1986). In order to maintain the cabin at this desired level of habitability we need to regulate the amount of air flowing into the cabin.

Within the cabin there is continuous gas exchange between the cabin air and the crew. The crew is continuously breathing in oxygen rich air and breathing out carbon dioxide rich air.

Hence prior to determining the air flow rate into the cabin it is imperative to calculate the mass flow rates and composition of the inspired and expired air. We propose to evaluate the mass flow rates and composition of the inspired and expired air based on the compartmental model of the human respiratory tract. The respiratory system of a human being includes the nose, nasal cavity and sinuses, the pharynx, the larynx, the trachea and smaller conducting passageways leading to the exchange surfaces of the lungs, (Martini, 1989). The inspired air which enters through the nose is filtered, humidified and warmed in the respiratory tract before reaching the alveoli in the lungs where gaseous exchange takes place. We shall now outline the procedure for modeling this entire respiratory mechanism.

We start with the compartment model of the human lung, (proposed by Seagrave 1971) to develop a more detailed model of the respiratory tract. It takes into account the volume and heat changes undergone by the inspired air by dividing the respiratory tract into three compartments. These are

(1) Upper respiratory tract where the inspired air is heated to the body temperature of 98.6 °F.

(2) Lower respiratory tract where the inspired air is saturated with water vapor. The partial pressure of water vapor at body temperature is 47mm Hg.

(3) Lungs, where O<sub>2</sub> which is required for metabolism is lost from the air to the blood in the pulmonary circuit and CO<sub>2</sub> which is produced during metabolism is added back to the air from the blood. Figure 7 depicts the model with all the input and output streams.

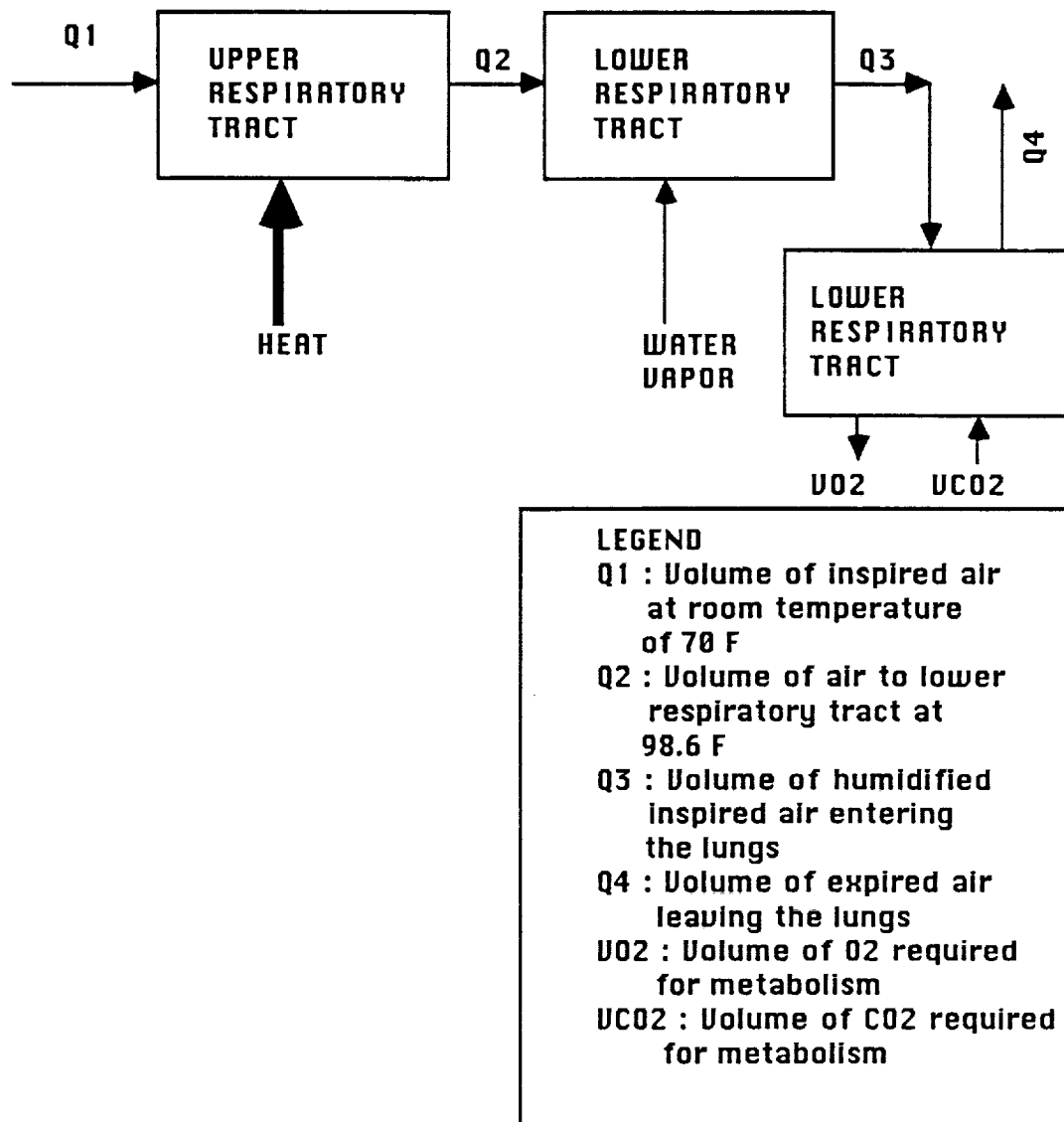


Figure 7: Compartmental model of the Respiratory tract.



The basic assumptions in our model are :

- (1) All the compartments are considered to be homogenous and well mixed so that concentration of each species at any time is uniform throughout each compartment.
- (2) The total pressure of air at any position within the respiratory tract is 760 mm Hg.
- (3) Ideal gas law holds in each compartment.
- (4) The total volume of oxygen required for metabolism does not rise above 3 lit/min at any instant, i.e the maximum permissible exercise limit of the crew is about 12 times the basal metabolic rate.

In our model we will follow only four significant molecular species in the gas and assume that any other species are present in negligible amounts. The four species to be followed are nitrogen, oxygen, carbon dioxide and water. The fundamental principle which is used to compute the mass flow of each species is

$$\begin{array}{lcl} \text{rate of} & = & \text{input flow rate} + \text{generation} - \text{degradation or} \\ \text{accumulation} & & \text{or production} \quad \text{consumption} \end{array}$$

Since this is a steady state model the rate of accumulation is equal to zero. The detail of equations used for each compartment is given in Appendix 1.

#### Upper Respiratory Tract

No material exchange is taking place. The inspired air is heated to body temperature. The relation between the volume of air entering and leaving the compartment is given as

$$Q_1 = 1.054 \times Q_2 \quad (19)$$

where  $Q_1$  is the volume of air entering in liters per hour  
 $Q_2$  is the volume of air leaving in liters per hour.

### Lower Respiratory Tract

The heated inspired air is saturated with water vapor. The volume of air leaving the compartment can be expressed as

$$Q_3 = 1.045 \times Q_2 \quad (20)$$

where  $Q_3$  is the volume of air leaving the compartment in liters per hour.

Knowing that the air leaving the compartment has a partial pressure of water of 47 mm Hg and that there is no exchange of other species namely oxygen, carbon dioxide and nitrogen, the mole fractions of the components in the gas exiting the lower respiratory tract is calculated as

$$\text{Mole fraction of oxygen ( } Y_{O_2^i} \text{ )} = 0.199$$

$$\text{Mole fraction of nitrogen ( } Y_{N_2^i} \text{ )} = 0.735$$

$$\text{Mole fraction of carbon dioxide ( } Y_{CO_2^i} \text{ )} = 0.004$$

$$\text{Mole fraction of water ( } Y_{H_2O^i} \text{ )} = 0.062$$

### Lungs

The following material balance equations can be written for the lungs.

Volume of  $O_2$  inspired = Volume of  $O_2$  expired + Volume of  $O_2$  lost to blood

$$0.199 Q_3 = Q_4 \times Y_{O_2} + V_{O_2} \quad (21)$$

Volume of  $CO_2$  inspired = Volume of  $CO_2$  expired - Volume of  $CO_2$  gained from blood

$$0.004 Q_3 = Q_4 \times Y_{CO_2} - V_{CO_2} \quad (22)$$

Volume of  $N_2$  inspired = Volume of  $N_2$  expired

$$0.753 Q_3 = Q_4 \times Y_{N_2} \quad (23)$$

Mole fraction of gases in expired air = 1.0

$$Y_{CO_2} + Y_{N_2} + Y_{O_2} = 0.938 \quad (24)$$

where

$Y_{CO_2}$  is mole fraction of  $CO_2$  in expired air

$Y_{N_2}$  is mole fraction of  $N_2$  in expired air

$Y_{O_2}$  is mole fraction of  $O_2$  in expired air

$Q_4$  is volume of expired air in liters per hour

From Figure 8, (Passmore and Robson, 1969) it is found that pulmonary ventilation ( $V_E$ ) increases in proportional to volume of  $O_2$  uptake at STP upto a certain point which is equal to 3 liters per minute of  $VO_2$  beyond which  $V_E$  increases more than the corresponding  $O_2$  uptake.

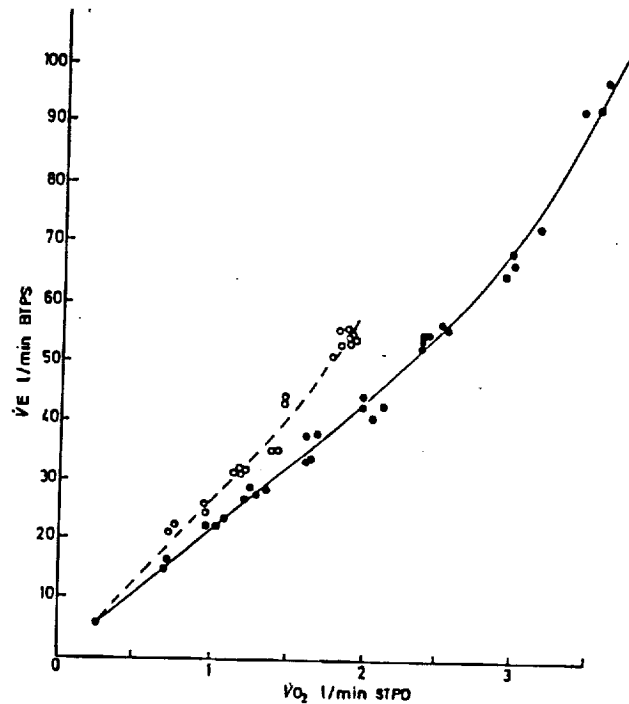


Figure 8:  $V_E$  in relation to  $VO_2$  (Adapted from Passmore and Robson, 1969)

In accordance with our third assumption it is justified to assume a linear relationship for  $O_2$  uptake and  $V_E$ . This is given by

$$V_E = 24.55 \times MO_2 + 0.1125 \quad (25)$$

where  $V_E$  is volume of gas entering the lungs in liters per minute at body temperature and saturated conditions  
 $MO_2$  is volume of  $O_2$  required for metabolism in liters per minute at STP and dry conditions

Knowing the volume of inspired and expired air and their respective mole fractions, we employ the ideal gas relation (  $PV = mRT/M$  ) to calculate the total mass flow rate of each gaseous component in expired and inspired air.

#### ASPEN model of the cabin

For modeling purpose the cabin is modelled as two compartments in series. The inputs and outputs of each compartments is shown in Figure 9.

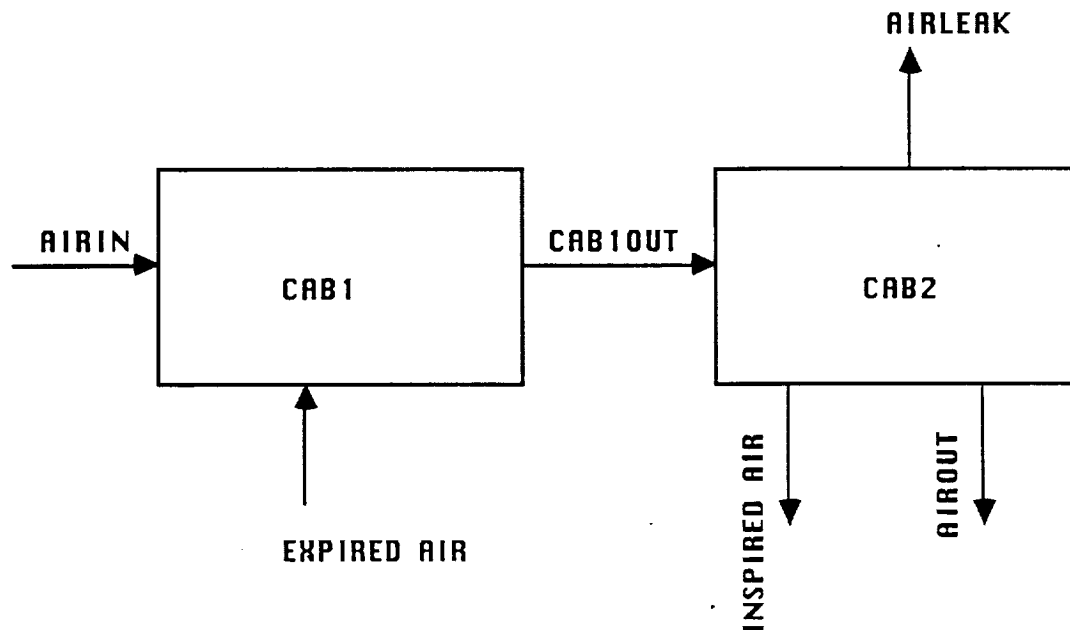


Figure 9: Model of Crew Habitat

There is a constant leakage of  $6.5 \times 10^{-4}$  lb/hour of gas from the cabin, (LiSSA,1992).

For the purpose of maintaining a comfortable living condition within the cabin we need to regulate not only the composition of air within the cabin but also the temperature and air motion. The design flow rate of air into the cabin is calculated from the following relation, ( Haines,1988)

$$CFM = \frac{q_s}{TD \times AF} \quad (26)$$

where

CFM is design flow rate in cubic feet per minute

$q_s$  is sensible cooling load in btuh

TD is design temperature difference between cabin and supply air

AF is the air factor

The Air Factor is used to take into account the variation in air density. The Air Factor is given by, (Haines, 1988) :

$$AF = \text{Density} \times SH \times 60 \quad (27)$$

where                      Density is air density at design temperature and pressure  
                                  SH is specific heat of air, btu per lb, at design temperature  
                                  and pressure

For standard conditions, AF is equal to 1.08 btuh/cubic feet per min °F

As considerable energy will be expended in cooling the supply air to a low temperature we assume that the supply air is nearly at the room temperature of 69°F..

The cooling load is equal to the amount of heat lost by the crew. Since the crew is at a steady temperature the total heat lost by the crew is equal to their metabolic activity.

The ratio of CFM and inspired air is then used as a basis to preset the ratio between INSPIRED AIR and AIROUT.

In the ASPEN model the first compartment (CAB1) was modelled as a MIXER and the next compartment (CAB2) was modelled as FSPLIT with the volume ratio between INSPIRED AIR and AIROUT being predetermined. A feedback control mechanism was used to regulate the amount of air flowing into the cabin. The mass flow rates of the different gaseous components in the inspired air were the set variables, while the corresponding mass flowrates of the air into the cabin i.e AIRIN were the manipulated variables. This was accomplished in our ASPEN model using Design Specifications.

## 4 MODELING ECLSS SUBSYSTEMS

This chapter discusses different functional units comprising each subsystem of the closed loop ECLSS. Though each subsystem can have a wide variety of technologies, for our modeling purpose either one or two sample technologies were chosen for each subsystem. The modeling technique adopted was either to simulate each major piece of equipment or to simulate the functional performance of the functional unit.

For our modeling purpose we used ASPEN. The reasons for choosing ASPEN over other chemical process simulators, were elucidated in chapter 2.

However certain difficulties were encountered in modeling with ASPEN. ASPEN is not equipped to provide detailed models of electrolyte process, so the electrolysis model, as in water electrolysis process, lacks fidelity in kinetic characterization of electrode reactions. No provision is made in ASPEN for the participation of electrons in the electrode reactions so the cell reactions are modelled as chemical rather than electrochemical process.

Another difficulty is encountered in modeling membrane technologies. ASPEN has no routines for modeling membrane based separations. The membrane based CO<sub>2</sub> removal system was therefore modeled using a user written FORTRAN block.

Lastly, ASPEN is a steady state modeling tool and so difficulties are to be encountered in modeling dynamic process.

### Water Reclamation Subsystem

Water reclamation involves process to reclaim water from sources such as carbon dioxide reduction, cabin humidity condensates, wash water ( from clothes, dishes

and hygiene ) and urine. Usually the average flow rates of wash water and urinal flush water are taken as 12 lb/day and 1.09 lb/day respectively, (NASA database,1992 ).

The flow rate of urine is determined from the metabolic rate of the crew (shown in chapter 3 ). The procedure to calculate the amount of humidity condensate will be outlined in the section on Atmosphere Humidity Control.

The basic functions of the water reclamation system can be listed as, (Huttenbach and Radford, 1965) :

- Collection of waste water.
- Pre-treatment of waste water to inhibit the growth of bacteria and improve the performance of phase change process.
- Reclamation of water using a multifiltration, membrane or phase change process. In general membrane and multifiltration processes are used to treat less contaminated streams such as humidity condensate and CO<sub>2</sub> reduction process as while phase change processes are used to recover water from urine and hygiene water.
- Post treatment of recovered water to remove residual contaminants.
- Storage, distribution and thermal conditioning of recovered water.
- Monitoring the quality of recovered water.

#### Multifiltration

A multifiltration process includes a particulate/bacterial filter, an activated charcoal canister, an anion exchange resin bed and a cation exchange resin bed, (Popoma and Collins, 1965).



### Membrane Process

Membrane Process include Reverse Osmosis and Electrodialysis. Generally spiral wound, tubular and tube side hollow fiber membranes are used. The membrane processes have the advantage of less power consumption and heat rejection over conventional phase change process. However, they have the disadvantage that the water to be treated by these processes require a greater degree of pretreatment as compared to conventional phase change process. Moreover, most conventional membranes are unable to withstand high temperatures sufficient for sterilization (Schubert, 1983).

### Phase Change Process

Phase change processes involve distillation and condensation, with a goal to retain the solutes ( in sterilized form ) in the evaporator and to reclaim the energy required for the vaporization process. The phase change processes that are commonly used are air evaporation, vapor compression distillation, thermo electric integrated membrane evaporation subsystem, and vapor phase catalytic ammonia removal.

Since phase change processes are used for the treatment of bulk waste water such as urine and hygiene water, we have only considered the phase change process for our water regeneration process. Two sample technologies which were studied are **Vapor Compression Distillation ( VCD )** and **Thermo electric Integrated Membrane Evaporation Subsystem (TIMES )**.

### Vapor Compression Distillation

Process Description :

A schematic of a VCD is shown in Figure 10. The recovery of latent heat in the VCD is accomplished by compressing the vapor to raise its saturation temperature and

then condensing the vapor on a surface which is in direct contact with the evaporator. The resultant heat flux from the condenser to the evaporator is sufficient to evaporate an equal mass of water. Thus the latent heat of condensation is recovered by the evaporation process and the only energy required for the process is that necessary to compress the vapor and to overcome the thermal and mechanical inefficiencies. The VCD process occurs in a 70°F to 95°F temperature range by maintaining a nominal condenser pressure of 0.7 psia, (Quattrone, 1981).

As shown in Figure 10, there are two tanks, the recycle tank and the waste water tank which are maintained at a pressure of 20 psia. The still is evacuated to a saturation pressure of 0.5 psia operating at a temperature of 70 °F. Pretreated urine and waste water are stored in the waste water tank and is then sent to the recycle tank. The process is continued till the solids concentration in the recycle loop increases to greater than 50%. The process is then stopped, the brine is removed and the VCD is then restarted.

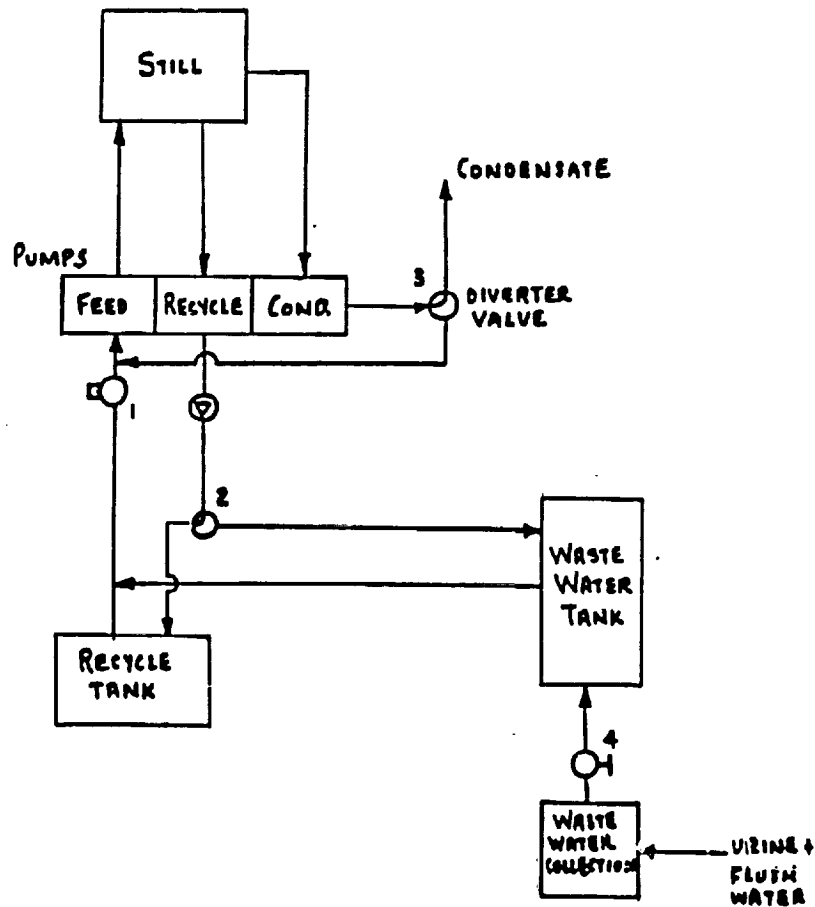


Figure 10 : Schematic of VCD (Adapted from design proposed by Lockheed INC)

The ASPEN model of the VCD is shown in Figure 11. The evaporator and the condenser are modeled as a combined unit using a SEP block. This is valid because there is no heat exchange from the environment for the combined unit. Since ASPEN can only model a steady state process, we have assumed that a 50% concentrated brine is obtained from the evaporator. This eliminates the presence of a recycle loop. This model predicts a 99.8% recovery of waste water which is greater than the literature values of 96%, (Schubert, 1983).

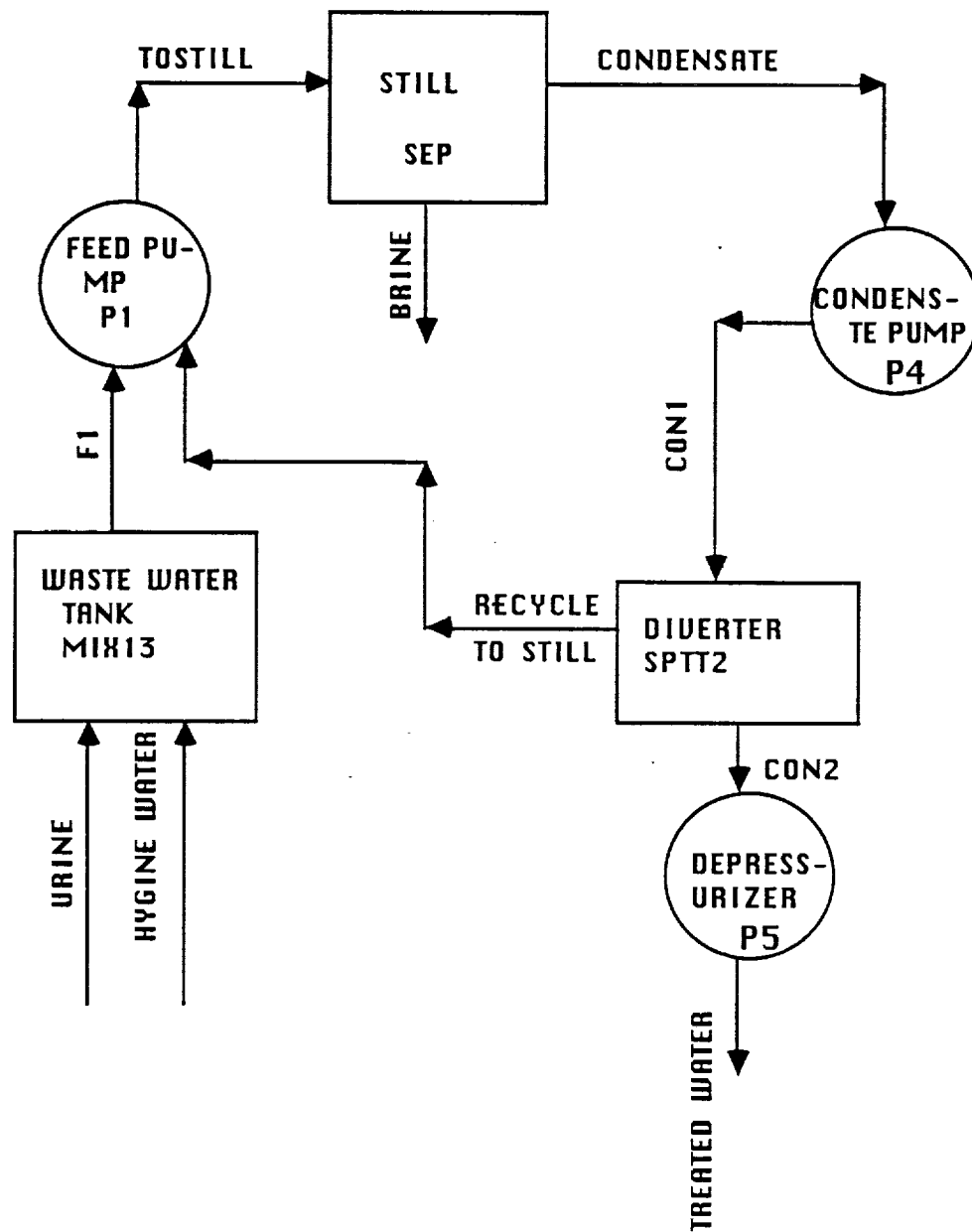


Figure 11 : ASPEN model of VCD

Thermo electric Integrated Membrane Evaporator Subsystem ( TIMES )

Process Description (Winkler, 1982) :

The TIMES is a vacuum distillation subsystem that combines a hollow fiber membrane evaporator with a thermo electric heat pump.

The waste water is first pretreated with sulfuric acid/chromium trioxide solution to provide bacteria control. It is then heated to near the pastuerization temperature of 150 °F by a heat exchanger in contact with the hot junction surfaces of a thermo electric heat pump. The heated waste water then passes through a tubular hollow fiber membrane evaporator. The outside surface of the membrane tubes are exposed to a low pressure of 2.47 psia. Water diffuses through the tube walls and evaporates, forming steam at the tube outer surface while other liquid and dissolved solid constituents of the waste water remain in the recycle loop. The slightly cooled and concentrated waste water is then returned to the recycle tank. The solids concentration in the recycle loop gradually increases until a solids concentration of around 40% is reached. At this point the process is stopped, and the recycle tank and the filter are removed using maintenance probes. Fresh recycle tank and filter units are installed and the process is continued.

Evaporated steam is condensed to water on a chilled porous plate surface that thermally contacts the cold junction surface of the thermo electric heat pump. The condensate is then drawn into an accumulator. Figure 12 shows the schematic of the process.

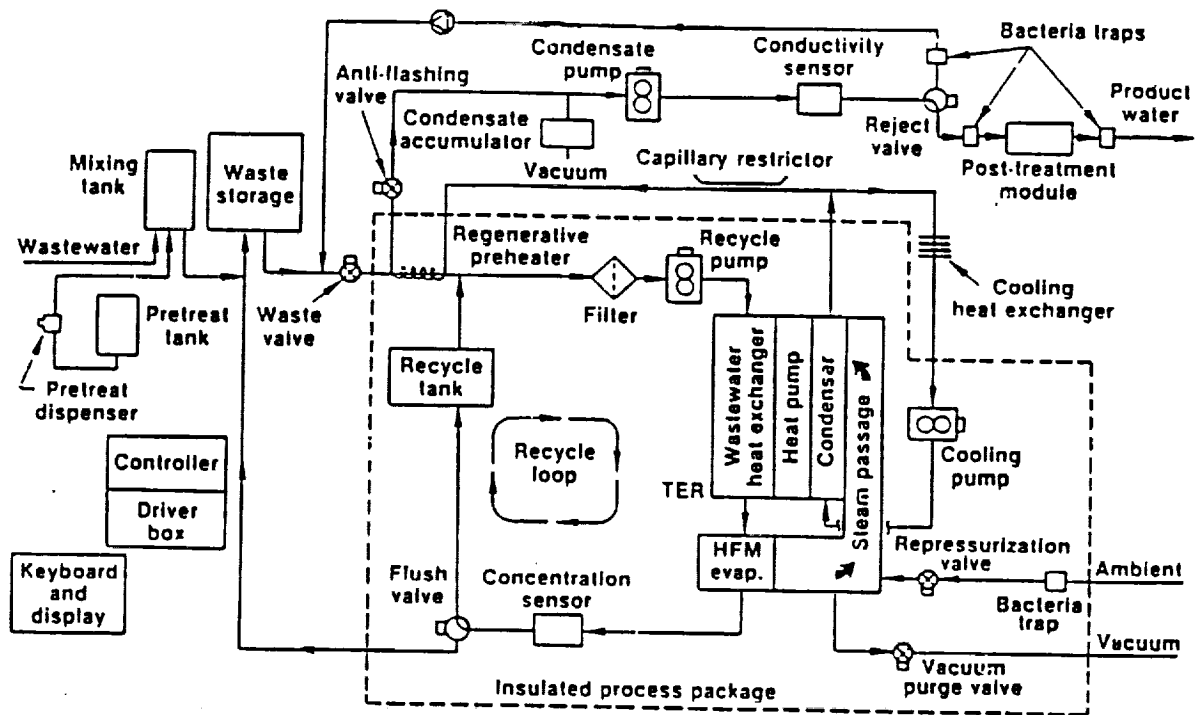


Figure 12: Schematic of TIMES (Adapted from Winkler et al., 1982)

The ASPEN model of the process is shown in Figure 13. Our approach here is to model the nature of the operation of TIMES, not the actual unit operation blocks involved. The thermo electric junction is modeled using two heaters, one for the hot junction and the other for the cold junction with heat being transferred from the hot to the cold junction. Since ASPEN has no tailor made blocks to model membrane separation we use a SEP block to simulate the operation of the membrane separator. The steam leaving the evaporator is saturated at the evaporator temperature. From the steam tables the saturation pressure of the steam is 3.784 psia. For the purpose

of developing a steady state model we assume that the brine from the evaporator is 40% concentrated with solids and that there are no recycle loops. Predicted recovery of waste water from our simulation calculation is 99.7%.

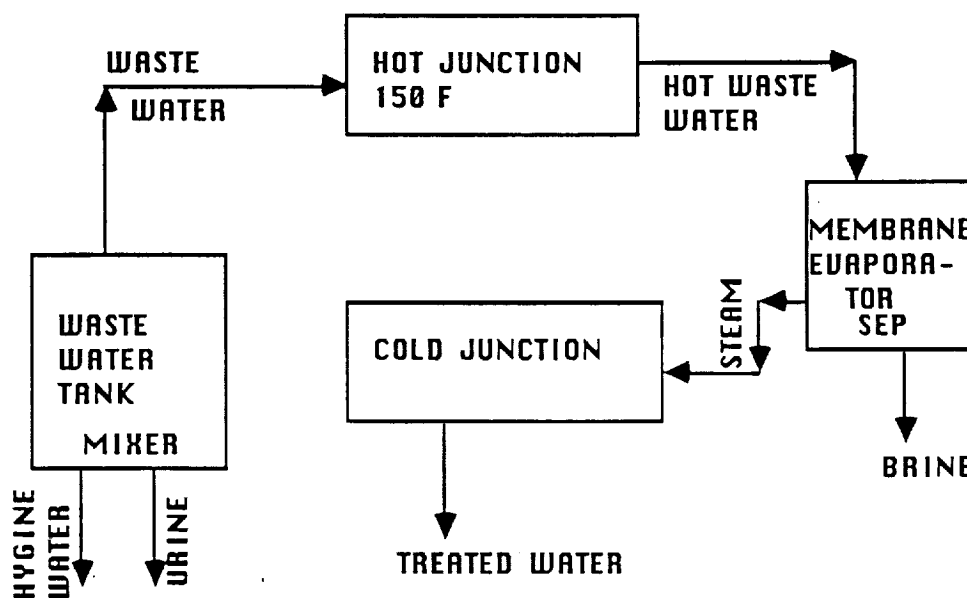


Figure 13 : ASPEN model of TIMES

### Air Revitalization System

The air revitalization system ( ARS ) is a critical component of the life support structure on a spacecraft or a planetary base. The ARS controls the temperature, pressure and composition of the cabin. The subsystems included in the ARS are Trace Contaminant Removal, Humidity Control, CO<sub>2</sub> removal and reduction and N<sub>2</sub> and O<sub>2</sub> production, storage and distribution. Different modules are available for each subsystem. We shall now give a brief outline of the process schematic of each module followed by its ASPEN model.

### Trace Contaminant Removal Subsystem

Contaminants in a manned space craft emanate from both the crew and the equipment. As mission durations, vehicle sizes, crew sizes, vehicle payload and experimental complexities increase and as the space craft leak rates decrease there will be a concomitant increase in the concentration of the trace stream. For our modeling purpose the flow rate of the contaminant stream was multiplied by the size of the crew. The following technologies are available for contaminant removal , ( Ammann , 1989) :

- condensing heat exchanger
- freeze out
- decomposition by corona discharge
- adsorption on molecular sieves
- catalytic oxidation
- chemisorption

Table 2 shows the generation rates of the different trace stream components. This is based on a basis of 1 crew member.



Table 2 Composition of Trace Contaminant Stream (Adapted from Ammann,1989)

Component	G [ mg/day ]
CO	3000
CH <sub>4</sub>	300
C <sub>2</sub> H <sub>6</sub>	2
C <sub>2</sub> H <sub>4</sub>	0.05
C <sub>2</sub> H <sub>2</sub>	0.5
H <sub>2</sub>	260

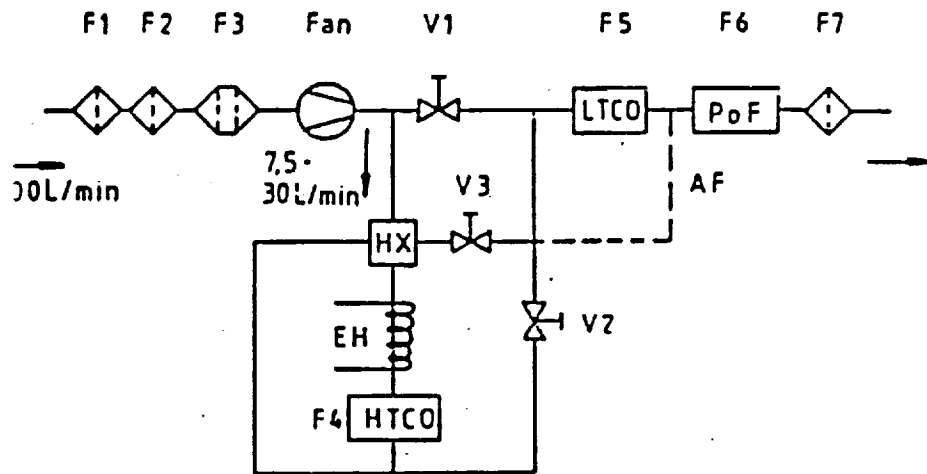
For our study the catalytic oxidation process was chosen.

#### Catalytic Oxidation Process

##### Process Description :

Figure 14 shows a schematic of the process. The process air initially passes through a pre filter which removes the harmful substances present like ammonia or freon which act as catalyst poisons. The bulk of air then flows into the LTCO ( Low Temperature Catalytic Oxidizer ) which operates at ambient temperature. The CO is oxidized in the LTCO. A small portion of the air which is adjustable, depending on the CH<sub>4</sub> concentration ( i.e higher the CH<sub>4</sub> concentration the greater the flow rate) flows into the HTCO (High Temperature Catalytic Oxidizer). Prior to entering the HTCO, the bypass flow passes through a heat exchanger (HX) and an electrical heater (EH). The temperature to be maintained in the HTCO is between 400 - 450°C. In the HTCO all the higher hydrocarbons present in the trace gas are oxidized. The

recombined flow from the HTCO and the LTCO leaves via a post filter, the purpose of which is to adsorb the acid decomposition products which are generated by catalyst contact and the outlet particle filter.



- F1** Prefilter Module 1/(Charcoal filter CCF)
- F2** Prefilter Module 2/(Charcoal filter CCF)
- F3** Prefilter Module 3/(Charcoal filter CCF with Particle Filter PF1)
- V1-V3** Valves
- HX** Heat Exchanger
- EH** Electrical Heater
- F4** High Temperature Catalytic Oxidizer
- F5** Low Temperature Catalytic Oxidizer
- F6** Postfilter
- F7** Outlet Particle Filter (PF2)
- AF** Alternative Feedback of HTCO By-Pass

Figure 14: Schematic of the Catalytic Oxidizer Process (Adapted from Ammann,1989)

The ASPEN model of the Catalytic Oxidation technology is shown in Figure 15. A user written Fortran block is used to determine the split fraction of gas going into the HTCO. The split fraction depends on the  $\text{CH}_4$  concentration in the feed and varies from 0.075 to 0.3. The two reactors were modeled using RGIBBS, which calculates reaction equilibrium based on Gibbs energy minimization.

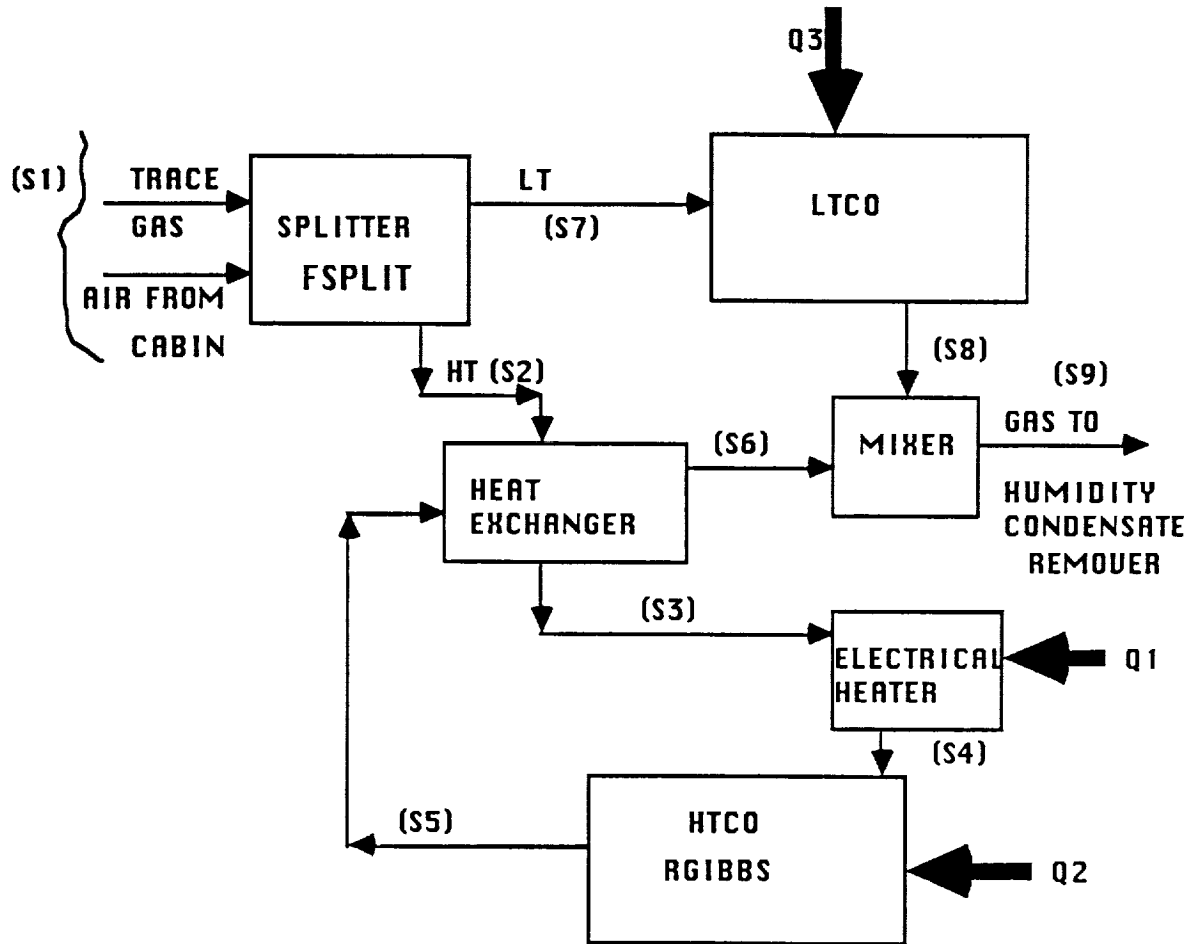


Figure 15: ASPEN model of the Catalytic Oxidizer Process

#### Atmosphere Humidity Control

The temperature and humidity of a habitat is to be regulated in order to provide a comfortable working environment. For our model we used a condenser-separator module to control the cabin humidity level. Our goal is to cool the gas from the trace removal subsystem to a temperature such that amount of water vapor in the exiting gas is equal to the amount of water vapor which is to be supplied to the cabin to maintain the cabin humidity level. The condensate is treated to obtain water of potable quality. The absolute humidity (mass of water/ mass of dry air) is thus known.

Determination of the temperature of the condenser involves an iterative technique, which involves reading enthalpy values of the gas and liquid water from psychometric charts.

This technique cannot be easily adopted for modeling purpose. For our modeling purpose we assume that the gas leaving the condenser is saturated with its moisture content. The temperature of the exiting gas is given by the following relation, (Treybal, 1988) :

$$t_{G2} = t_{G1} - \frac{\lambda}{C_s} (Y_{in} - Y_{out}) \quad (28)$$

where

$t_{G2}$	temperature of outgoing gas from condenser
$t_{G1}$	temperature of incoming gas to condenser
$\lambda$	latent heat of vaporization 1075.8 Btu/lb
$C_s$	humid heat
	$= 0.24 + 0.45 Y_{in}$ Btu/l (lb of air).°F
$Y_{in}$	absolute humidity of gas in
$Y_{out}$	absolute humidity of gas out

For the ASPEN model the condenser and the separator is modeled as a single unit using a SEP block. Knowing the absolute humidity of outgoing air the split fraction of the SEP block is determined in a user written FORTRAN block. Likewise, the temperature of the outgoing air is also determined using relation (28). A provision has however been provided for in the FORTRAN block that if the required temperature of the condenser falls below 40°F, the condenser temperature is to be set to 40°F. This option is provided to conserve energy.

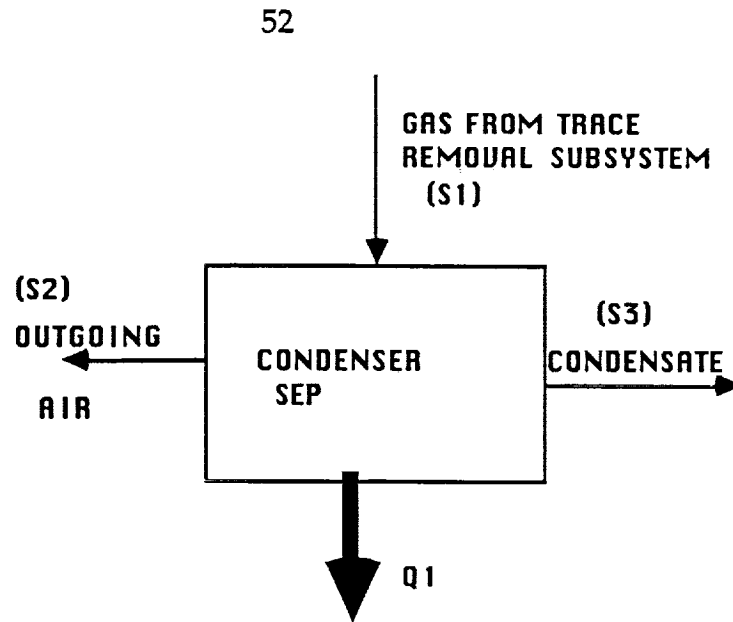


Figure 16: ASPEN model of Humidity Condensate Removal.

#### Carbon dioxide Removal Subsystem

According to the NASA requirement, in order to maintain comfortable living conditions in the crewed habitat the partial pressure of CO<sub>2</sub> must not exceed 3mm Hg, (Ray et al., 1987). In order to achieve this requirement the excess CO<sub>2</sub> in the air (generated due to food metabolism and in the trace removal subsystem) is removed in the CO<sub>2</sub> removal subsystem. The CO<sub>2</sub> that is removed is concentrated and then sent to the CO<sub>2</sub> reduction subsystem.

The commonly used CO<sub>2</sub> removal subsystems are :

- Solid-Amine Water desorbed CO<sub>2</sub> concentrator
- Electrochemical depolarized CO<sub>2</sub> concentrator
- 2 or 4 - Bed Molecular seive
- Metal oxide process where the CO<sub>2</sub> is complexed with a solid metal oxide
- Liquid - Sorbent / Membrane - Contactor system

For our study the Liquid - Sorbent / Membrane - Contactor system was chosen. The reasons for choosing this system are :

- light weight
- requires no consumables or expendables
- simple and does not rely on other ECLSS subsystems

Process Description (Mc Cray et al., 1990) :

CO<sub>2</sub> rich air is circulated through one side of the hollow-fiber membrane contactor and CO<sub>2</sub> is absorbed into the liquid sorbent, which is circulated on the other side of the membrane contactor. The CO<sub>2</sub> rich liquid sorbent is then sent to the second hollow fiber membrane contactor, where the CO<sub>2</sub> is removed using a vacuum compressor. The regenerated sorbent is then recycled to the absorption membrane contactor. A schematic of this process is shown in Figure 17.

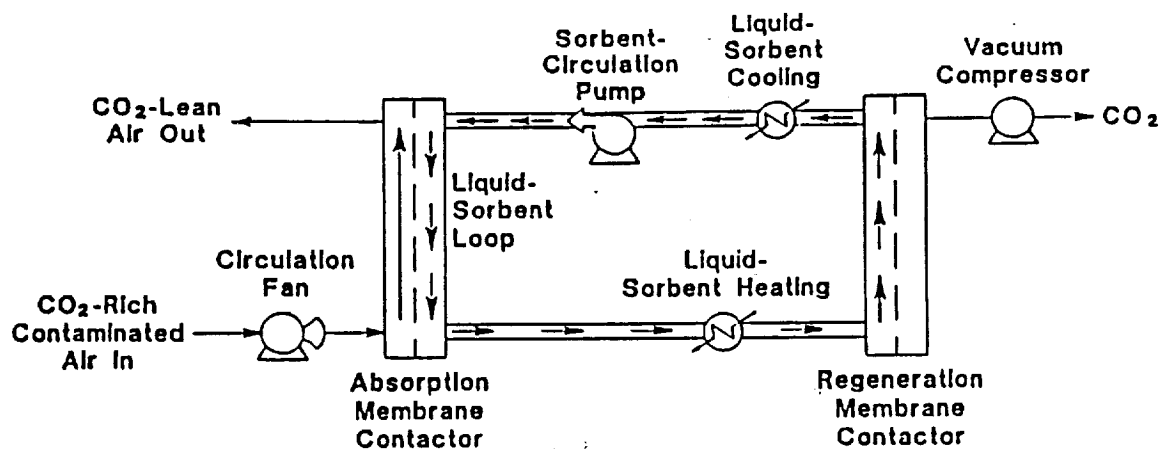


Figure 17: Schematic of Membrane based CO<sub>2</sub> removal system ( Adapted from Ray et al., 1990)

There being no tailor made blocks for membrane separators in ASPEN, our goal was to model the process objective rather than the actual unit operation. This was

accomplished by the use of a SEP block. The SEP block removes the CO<sub>2</sub> from the air which is in excess of the amount to be present in the cabin air in order to satisfy the cabin atmosphere requirements of 0.3% CO<sub>2</sub>. The separation degree of the SEP block is regulated by a user incorporated Fortran block. The air is cooled to 69°F before being sent to the cabin. The CO<sub>2</sub> is sent to the CO<sub>2</sub> reduction subsystem.

### Carbon dioxide Reduction Subsystem

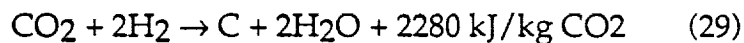
Among several technologies known for reducing CO<sub>2</sub>, the Sabatier and Bosch process are the two primary options being considered for application in a regenerable ECLSS. Both process reduce CO<sub>2</sub> by catalytic reaction with hydrogen. The Bosch process produces carbon and water while the Sabatier process produces methane and water. Following is a brief discussion of each of these processes.

#### Bosch CO<sub>2</sub> reduction

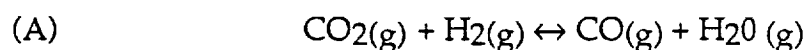
Detailed description of the Bosch process, its operation, specific hardware and performance are discussed extensively in the literature (Holmes, King and Keller, 1973, King and Holmes, 1976, Schubert, 1974, Manning and Reid, 1975). We shall give a brief summary of the process followed by its ASPEN model.

Process Description :

The Bosch reaction occurs at 800 to 1000K (980 to 1340 °F) in the presence of various catalyst such as iron, cobalt, nickel or ruthenium/iron alloys (Manning, Reid and Sophonpanich, 1982, Kolodney, Lange and Edeen, 1991). CO<sub>2</sub> combines with H<sub>2</sub> and produces carbon and water vapor as indicated in the overall reaction :



The reaction mechanism however involves several reactions :





- (B)  $\text{CO(g)} + \text{H}_2\text{(g)} \leftrightarrow \text{C(s)} + \text{H}_2\text{O(g)}$   
 (C)  $2\text{CO(g)} \leftrightarrow \text{C(s)} + \text{CO}_2\text{(g)}$   
 (D)  $\text{C(s)} + 2\text{H}_2\text{(g)} \leftrightarrow \text{CH}_4\text{(g)}$

Reaction A occurs first, the others can then occur in parallel. Reaction (C) may not be significant but reaction D is, (Minemoto et al., 1989). However it has been shown that if two reactors are used in series one operating at a higher temperature than the other, the  $\text{CH}_4$  concentration is negligible in all streams, (Minemoto et al., 1989). In practice, single pass efficiency through the bosch reactor is less than 10% for iron catalysts. Complete conversion is attained by recycling the processed gases with continuous deposition of carbon and removal of water vapor. Since all the reactants entering the subsystem are eventually converted to carbon and water, the overall stoichiometric ratio of two moles of  $\text{H}_2$  to one mole of  $\text{CO}_2$  must be maintained, (Spina and Lee, 1985). The schematic of the process is shown in Figure 18.

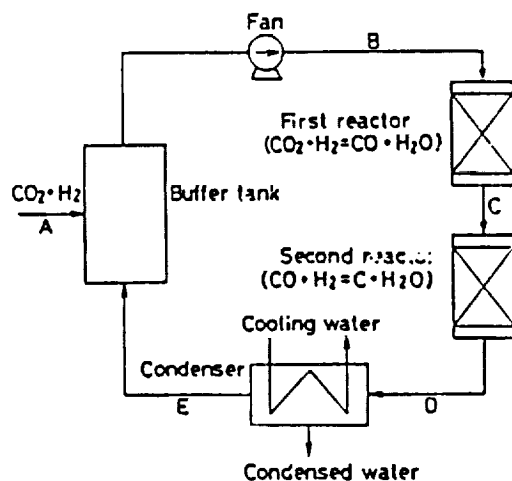


Figure 18: Schematic of Bosch process (Adapted from Minemoto et al., 1989)

The high purity CO<sub>2</sub> recovered by the CO<sub>2</sub> removal process and H<sub>2</sub> for the reduction are mixed, and this gas is taken to a buffer tank. Then the circulating fans channels the gas through the first and second reactors. The first reactor is maintained at a temperature of 1300 [K] while the other reactor is maintained at 900 [K]. In the first reactor reaction (A) occurs while reaction (B) is predominant in the second reactor. Methanation occurs to an appreciable limit in the second reactor. To prevent the accumulation of CH<sub>4</sub> within the subsystem which would eventually lead to a shut down of the process there is a bleed line connected to the trace removal subsystem. The solid carbon is collected in the second reactor, water vapor generated is condensed in the condenser and the unreacted gas is returned again to the buffer tank to be recycled again.

The reactors of the bosch system were modeled using the RGIBBS equilibrium reactor model. The validity in using RGIBBS is checked by estimating the conversion for a single pass ( i.e no recycle ). From the ASPEN model net conversion is found to be 37.6%. This is so because two reactors are used in series. Moreover in actual reactors 'graphite equilibrium' is usually not attained due to insufficient residence times and catalyst deactivation. Similar results were reported in literature, ( Sacco and Reid,1978 ). In our model, the H<sub>2</sub> feed rate is determined in a user written Fortran block to ensure CO<sub>2</sub>/H<sub>2</sub> stoichiometric ratio is satisfied. Figure 19 shows the ASPEN model of the Bosch system.

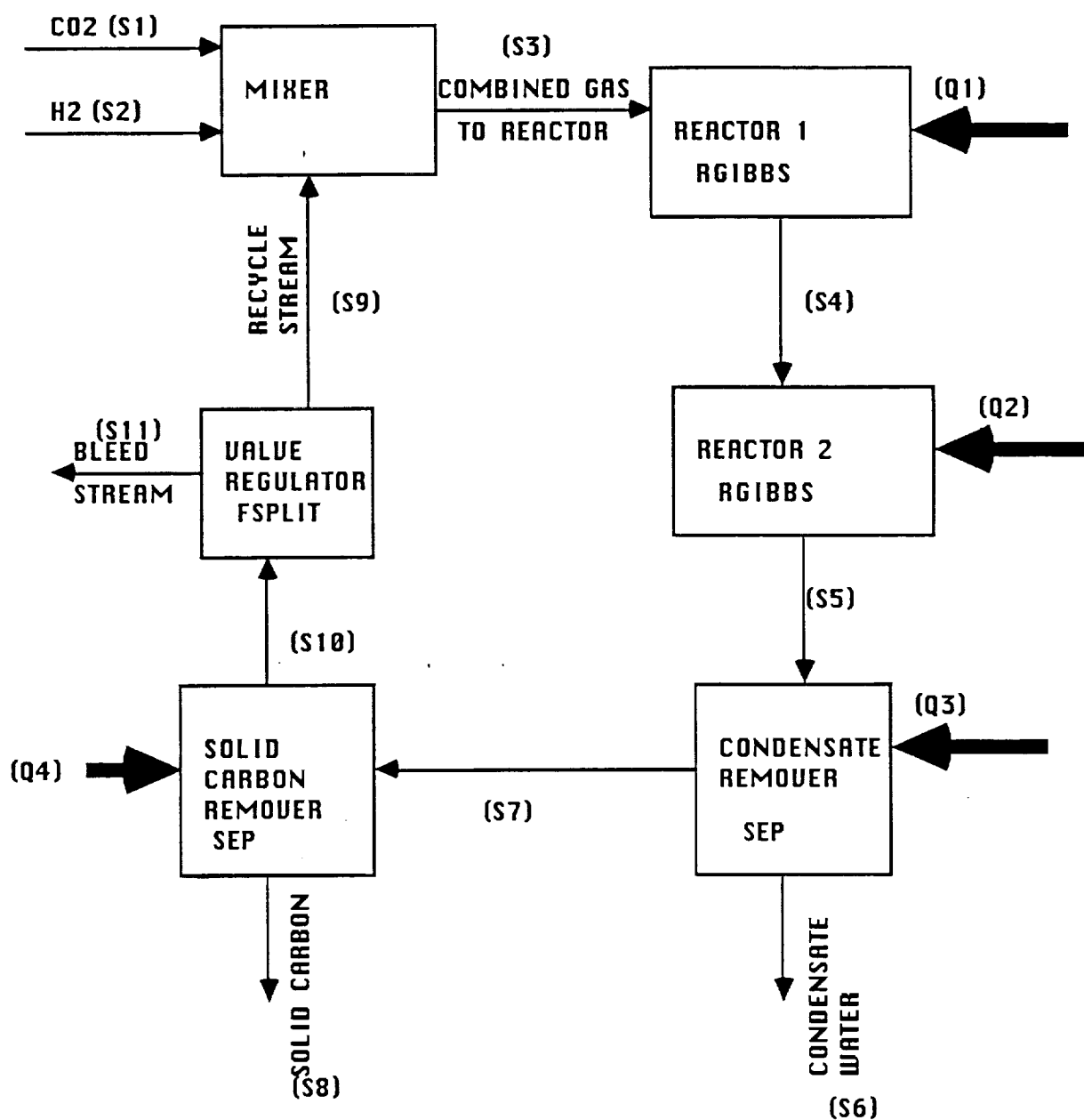
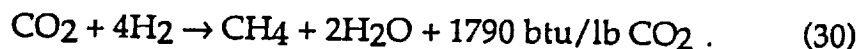


Figure 19: ASPEN model of Bosch system

### Sabatier Reactor

#### Process Description:

The Sabatier reaction occurs at 350 to 980 °F in the presence of catalyst. The reaction mechanism is shown below



With a stoichiometric reactant mixture the reaction efficiencies are higher than 98%, (Spina and Lee, 1985). So a single pass is always used for a Sabatier reactor. The methane and water vapor formed along with the excess reactants are cooled in the condenser where the water is condensed. The remaining methane and other gases are directed to the trace removal subsystem. Figure 20 shows the system schematic.

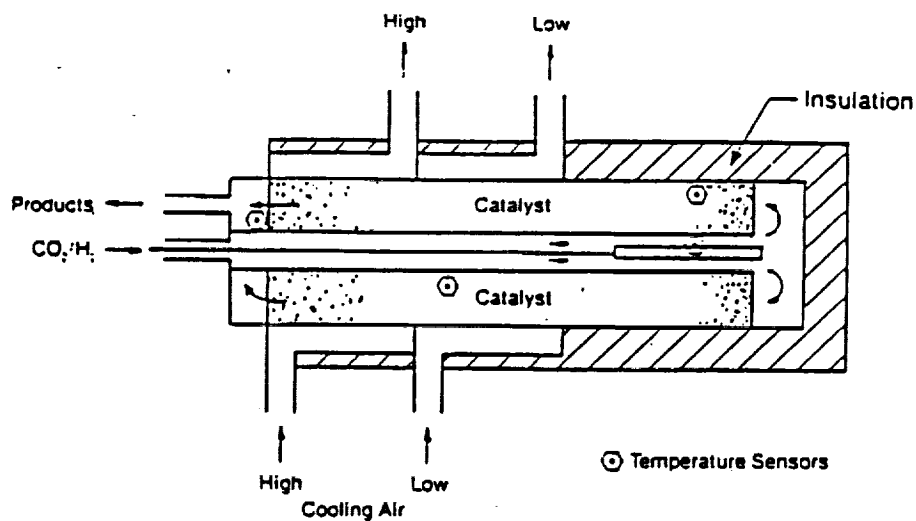


Figure 20 : Functional schematic of the Sabatier (Adapted from Spina and Lee, 1985)

The ASPEN model of Sabatier is shown in Figure 21. The reactor is modeled using a RSTOIC. The reason for choosing RSTOIC is that since the conversion per

pass in the Sabatier reactor is usually higher than 98% , a RSTOIC with a specified conversion of carbon dioxide of 98% can adequately simulate the real process. A user written Fortran block is incorporated to direct the stoichiometric amount of  $H_2$  to the reactor.

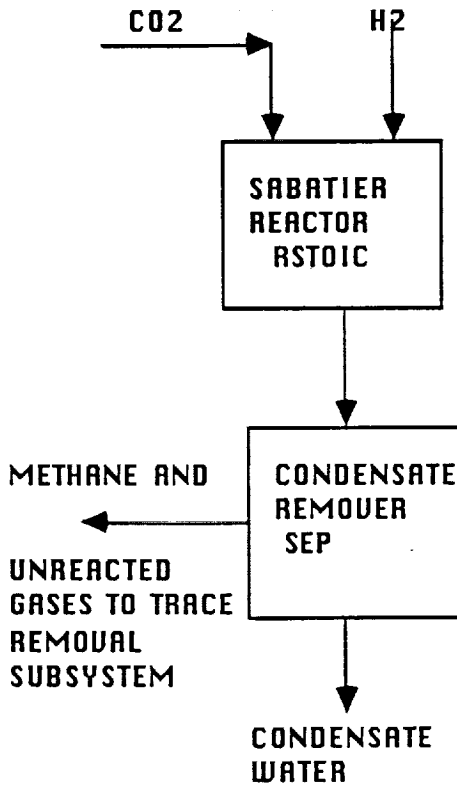


Figure 21: ASPEN model of the Sabatier

### Oxygen generation subsystem

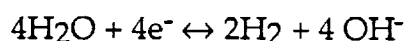
To meet the needs of the crew on board the space station  $O_2$  and  $H_2$  are to be supplied by an  $O_2$  generation assembly. Apart from metabolic consumption,  $O_2$  is required to make up for cabin leakage as well as air lock losses.  $H_2$  is required for

CO<sub>2</sub> reduction. For our study we have chosen the **Static Feed Water Electrolysis system.**

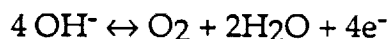
**Electrolysis Process :**

In a water electrolysis cell, water is dissociated into its elements by supplying electrons to a negatively charged electrode (cathode) to produce H<sub>2</sub> and removing electrons from a positively charged electrode (anode) to produce O<sub>2</sub>. The half-cell reactions for the water electrolysis cells using an alkaline electrolyte are shown below : (Fortunato et al., 1988)

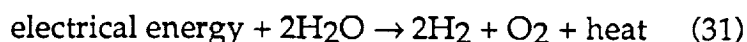
At the cathode :



At the anode :



Overall reaction :



### Static Feed Water Electrolysis

**Process Description :**

Initially the feed water compartment is filled with water and the electrolyte retention matrix is fully charged with aqueous electrolyte. As electrical power is supplied to the electrodes, water is electrolyzed from the electrolyte retention matrix. This increases the initial electrolyte concentration gradient between the water in the feed water compartment and the electrolyte in the electrolyte retention matrix. Water vapor then diffuses from the water feed membrane into the electrolyte retention matrix due to this gradient. Advantages of this system are :

- since there is no contact between the liquid feed water and the cell electrodes ultrapure water need not be used.

- the water feed membrane is liquid impermeable but water vapor and gas permeable eliminates any concerns regarding H<sub>2</sub> diffusion into the water cavity.
- no dynamic phase pump/separators are needed to remove the product gas from the feed water stream.

Table 3 shows the design requirements for the process.

Table 3      Performance Requirements of Static Feed Water Electrolysis unit  
(Adapted from Fortunato et al., 1988)

Parameter	Units	Operational mode
		H <sub>2</sub>
/O <sub>2</sub> partial pressure	psia	2.83 - 3.35
O <sub>2</sub> delivery pressure	psia	20± 5
H <sub>2</sub> delivery pressure	psia	25± 5
H <sub>2</sub> O supply temperature	F	65 - 80
H <sub>2</sub> O supply pressure	psia	30 - 45

Schematic of the Static Feed Water Electrolysis process is shown in Figure 22.

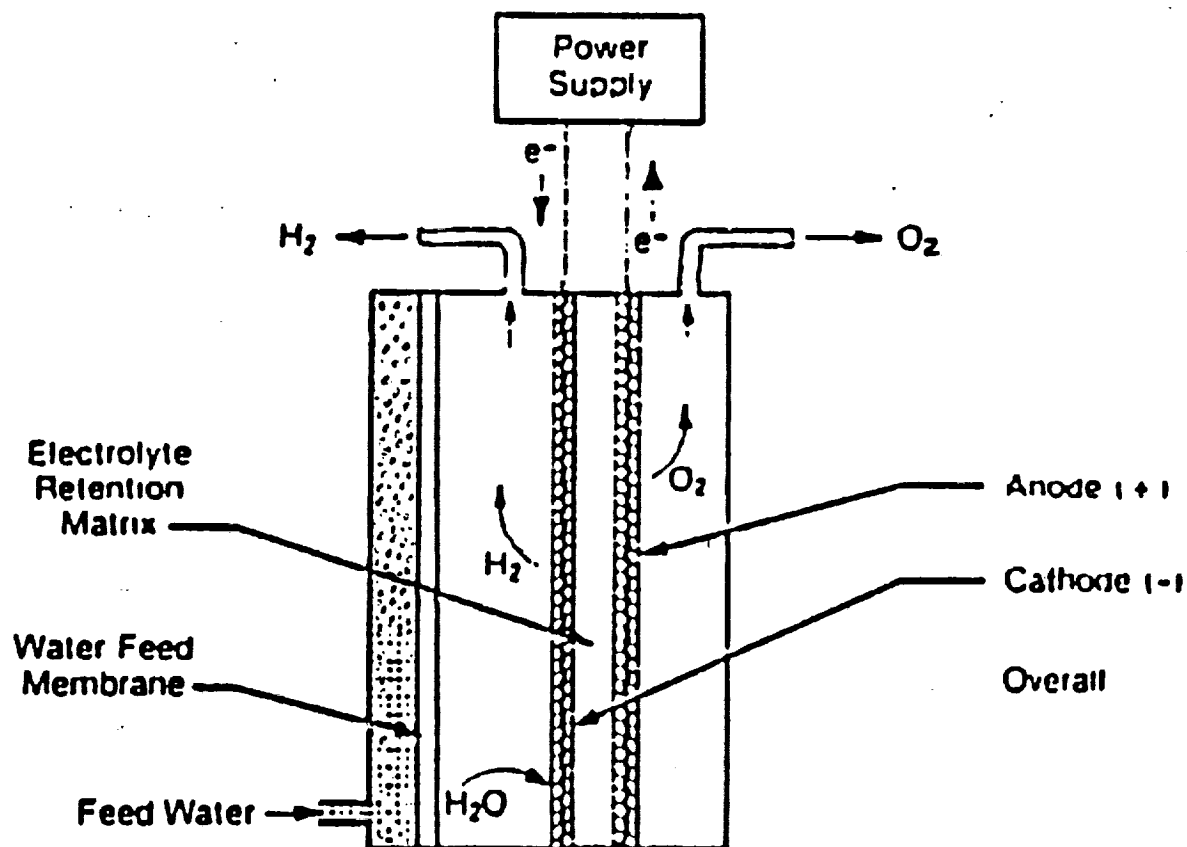


Figure 22 : Schematic of the Static Feed water Electrolysis process (Adapted from Fortunato et al., 1988)



For the ASPEN model of the Static Feed Electrolysis, the water from the water regeneration subsystem is pressurized to 30 psia before being fed to the water electrolyzer. A cooler placed before the electrolyzer removes the heat generated due to compression in order to supply water to the cell at the ambient temperature. Since ASPEN does not have any blocks to simulate the electrolysis process the overall process was modeled as a chemical reaction using a RSTOIC block with the reaction stoichiometry specified and the conversion of water set at 100%. The output from the electrolyzer is then sent to a SEP block which is a combination of a cooler, a depressuriser and a condenser. H<sub>2</sub> and O<sub>2</sub> are sent to their respective buffers. The ASPEN model of this process is shown in Figure 23.

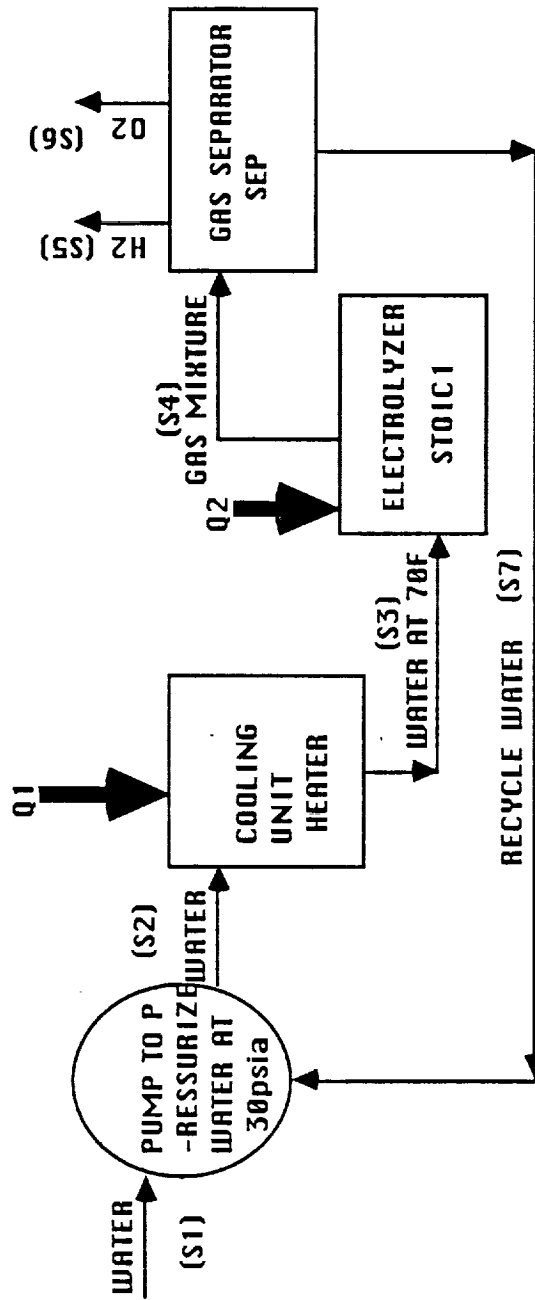


Figure 23: ASPEN model of Static feed water electrolysis

### Solid Waste Management

Waste management is required to control the accumulation of materials that would otherwise lead to breakdown of the life support system. Apart from solid wastes generated by the crew, the other physico - chemical processes which constitute the life support system generate typical solid wastes which include particle filters, product carbon catridges, depleted catalysts, contaminated adsorbents, wate filters, wicking units, chemical and multifiltration units. Various technologies which can be used for solid waste treatment range from use of chemical germicides to stabilize fecal bacterial gas production to complete oxidation of organic wastes, (Quattrone, 1981). Again there are two types of oxidation :wet oxidation and dry oxidation (incineration). For our modeling purpose we used the wet oxidation process.

### Wet oxidation Process

Process Schematic, (Takahashi and Ohya, 1985) :

Wet oxidation is a reaction in which organic or reductive compounds are oxidized in the presence of liquid water. This reaction occurs between 100 and 374 °C which is the critical temperature of water. The reaction is carried out in an autoclave to prevent evaporation of water. The pressure is set to 1067 psia. The added O<sub>2</sub> index is maintained at 1, i.e the exact quantity of O<sub>2</sub> is added to completely oxidize the raw materials. There is a linear relationship between % of carbon in waste and the temperature to be maintained in the oxidation process, (from Figure 1 of the paper by Takahashi and Ohya, 1985) . The linear relationship is :

$$\% \text{ of carbon in feed} = - 0.65 \text{ oxidation temp} + 194 \quad (31)$$

For the ASPEN model of the wet oxidation process, the oxidizer was modeled using a RSTOIC block. The temperature was determined from a user written Fortran block using the linear relationship of equation (31). We have assumed that only the carbon content of the waste is completely oxidized to  $\text{CO}_2$  while the nitrogen and the hydrogen components of the feed remain unchanged. Thus the ECLSS loop is not completely closed as far as nitrogen and hydrogen are concerned, and a buffer must be used.

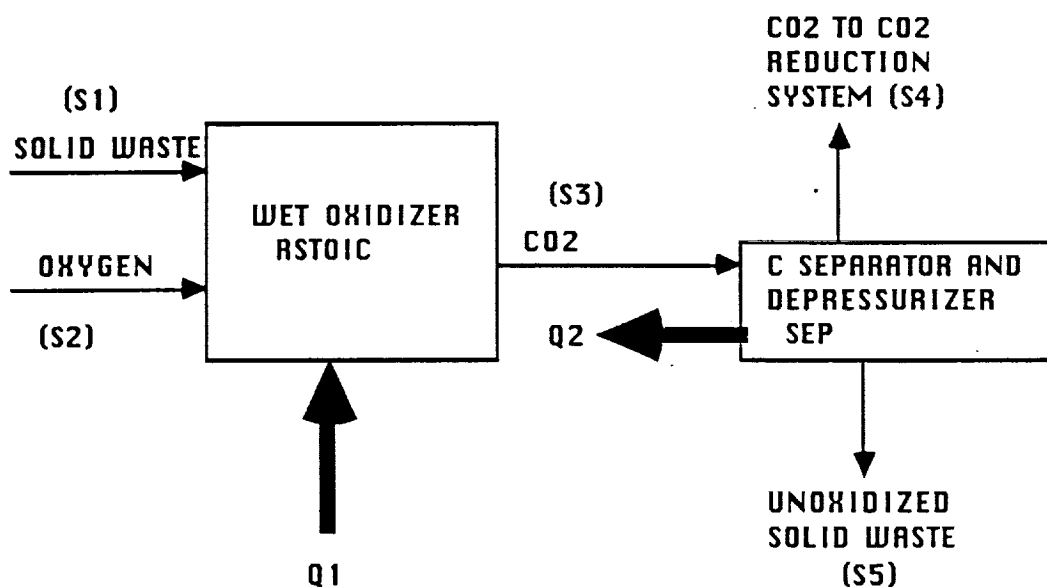


Figure 24: ASPEN model of the wet oxidation process

## 5 RESULTS AND DISCUSSIONS

In order to compare quantitatively the merits and demerits of storage vs regeneration of the critical constituents of a life support system (LSS) a detailed systems analysis is required. Herein, we present the results which were computed from the ASPEN model of the ECLSS, which give us a perspective of the requirements and design of the ECLSS. The results can be interpreted to arrive at three categories of information :

- Mass balance sensitivity of the ECLSS.
- Technology trade study
- Parameter sensitivity analysis

### Development of the integrated ECLSS model

As elucidated in Chapter 3, the crew is the primary producer of wastes. These wastes serve as inputs to the different life support modules. Since the objective of a regeneration design is to reduce the amount of expendables supplied, the wastes are processed in different LSS modules before being recycled back.

The crew specification will then influence the mass flow rates of the different components within the ECLSS.

It is thus imperative to provide an interactive environment for the crew model to study the mass flux values of the critical components under different scenarios. This was arranged by allowing the input variables like crew number, age, gender, height, weight and activity levels to be read from a user supplied data file.

As mentioned in chapter 2, the ECLSS consists of seven subsystems. The ECLSS modules are not water tight compartments but are closely connected to each other. The gaseous constituents and the water balances interact as :

- CO<sub>2</sub> reduction generates water which is processed to potable water

standards

- The bleed stream from the CO<sub>2</sub> removal process is directed to the trace removal subsystem.
- Humidity condensate from the humidity condensate removal subsystem is treated to obtain potable water.
- Part of the treated hygiene water is further treated to obtain makeup potable water and the remaining water is sent to the oxygen generation subsystem.
- The H<sub>2</sub> and O<sub>2</sub> from the O<sub>2</sub> generation subsystem are stored in their respective buffers
- The H<sub>2</sub> for CO<sub>2</sub> reduction is obtained from the H<sub>2</sub> buffer while the O<sub>2</sub> required for makeup O<sub>2</sub> in the cabin and for solid waste treatment is drawn from the O<sub>2</sub> buffer.

Figure illustrating the interaction between the LSS modules and the crew is included in Appendix 2.

In order to develop a complete ECLSS model which takes into account the interaction between the respective ECLSS subsystems, the ASPEN models of the different ECLSS subsystems (which were developed in chapter 4) were unified in a program. The user written crew model was then appended to the main program. The code is included in Appendix 3.

#### Mass Balance Sensitivity of the ECLSS

The utility of the type of LSS configuration chosen for the mission (e.g open loop, partially closed loop, or completely closed loop) can be gauged by estimating the flow rates of the critical components. Figures 25A, 25B and 25C show the variation in mass flow rates for three cases where,

Case 1: Completely open loop.

Case 2: Partially closed loop. No O<sub>2</sub> generation and CO<sub>2</sub> reduction subsystems are present. Food is supplied.

Case 3: Completely closed loop, however food is supplied.

It is to be noted that all the values shown in Figures 25A, 25B and 25C are for the baseline case of one man operating at basal metabolic rate.

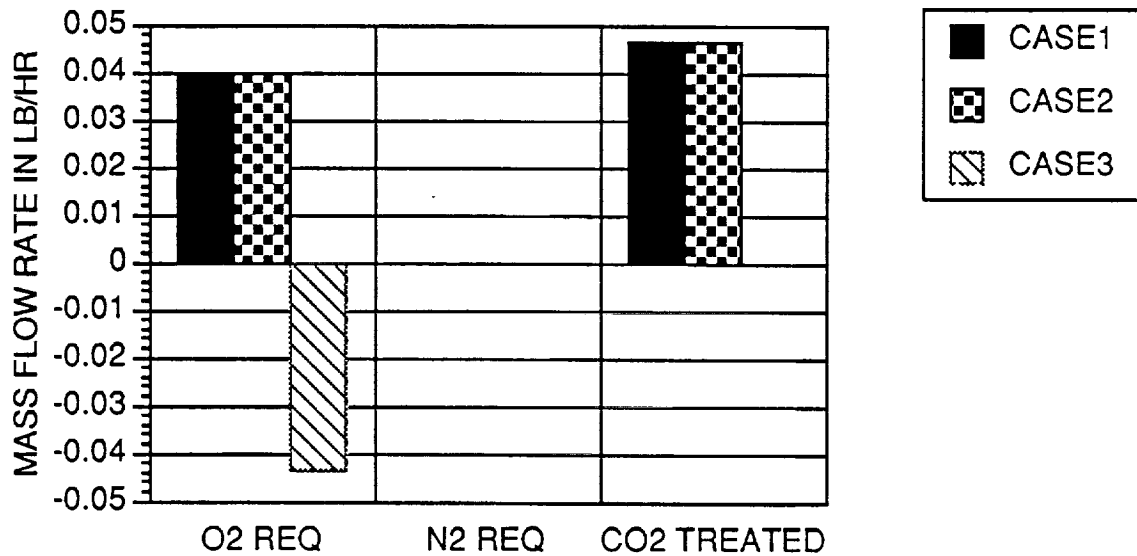


Figure 25A: O<sub>2</sub>, N<sub>2</sub> and CO<sub>2</sub> requirement for the three cases.

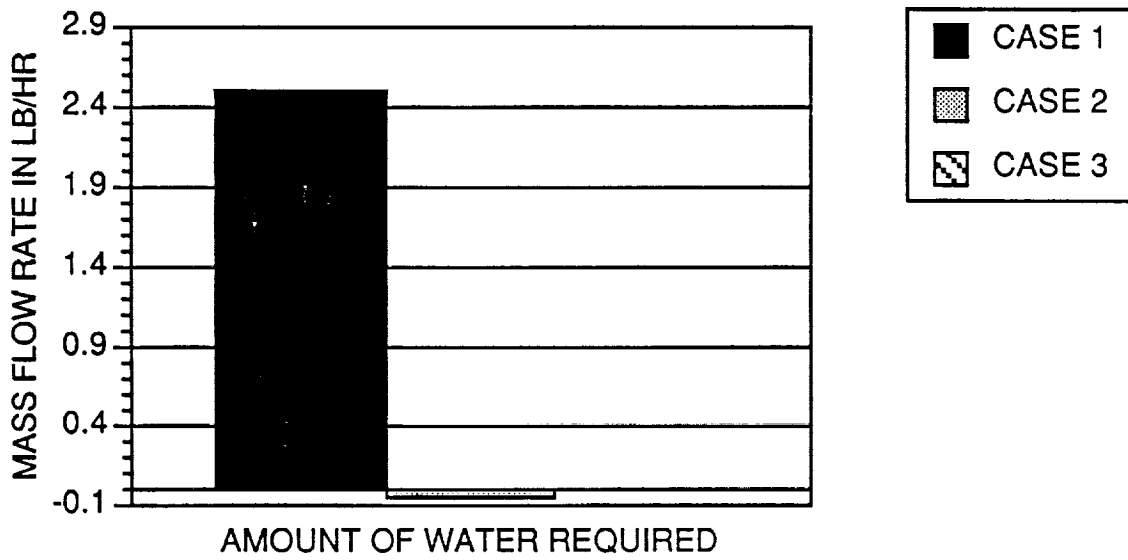


Figure 25B: Comparison of water requirement

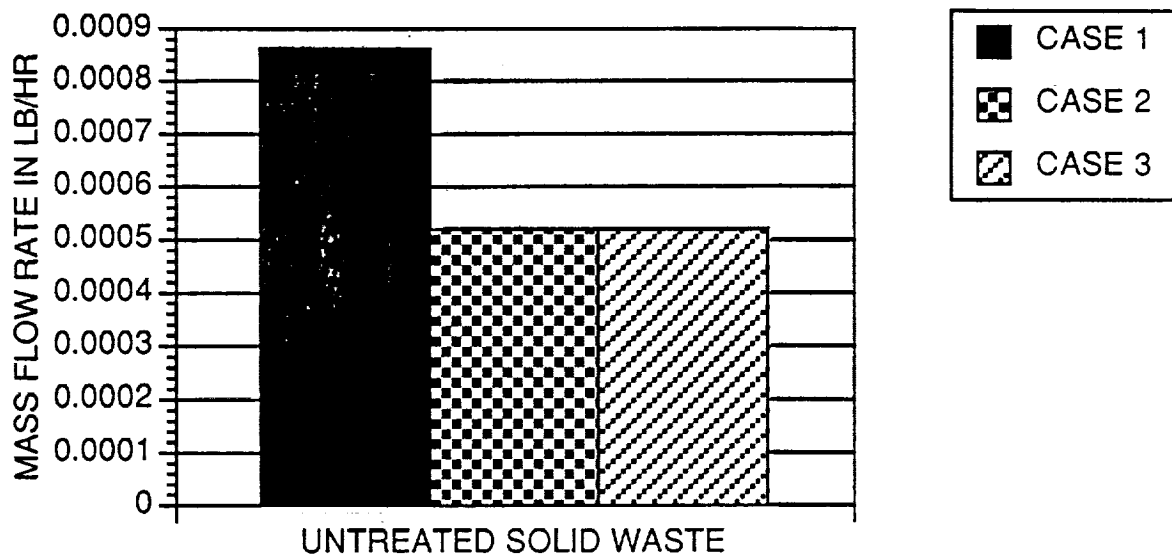


Figure 25C: Comparison of total untreated solid waste



It is observed from Figure 25A that with regard O<sub>2</sub> and CO<sub>2</sub> flow rates, the closed loop is advantageous to the other cases, as excess O<sub>2</sub> is produced which is stored in the buffer, and all the CO<sub>2</sub> which is produced is reduced within the system. The utility of the water regeneration subsystem is well illustrated in Figure 25B. The negative sign for the partially closed loop indicates that since there is no O<sub>2</sub> generation subsystem excess water is produced which is stored in the buffer. From Figure 25C it is evident that for a completely open loop the increase in amount of solid waste to be handled adds a greater burden to the system.

According to different crew missions the crew specification changes. Thereby, in order to arrive at a preliminary estimate of the sizing of the different ECLSS functional units and storage tank capacity, it is essential to know the mass-flow rates of the substreams within the ECLSS. Figures 26A, 26B and 26C show the variation in mass flow rates of the critical components with changing scenarios.

Case 1 : 1 man operating at basal metabolic rate

Case 2 : 1 man operating at 4 times the basal metabolic rate

Case 3: 1 man operating at 4 times basal metabolic rate and 1 woman operating at 3 times the basal metabolic rate.

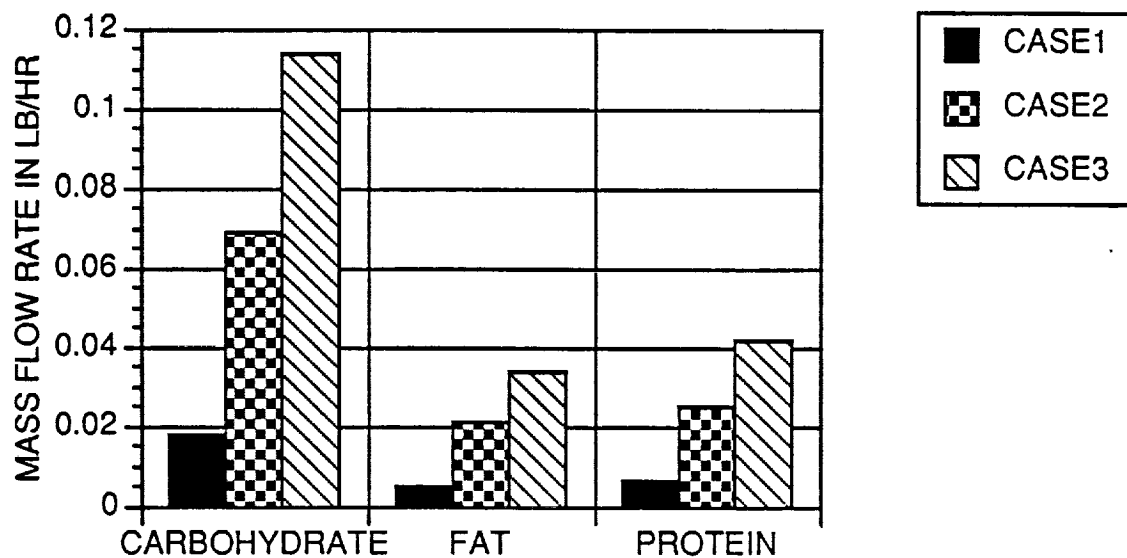


Figure 26A: Comparison of food requirement for the three cases.

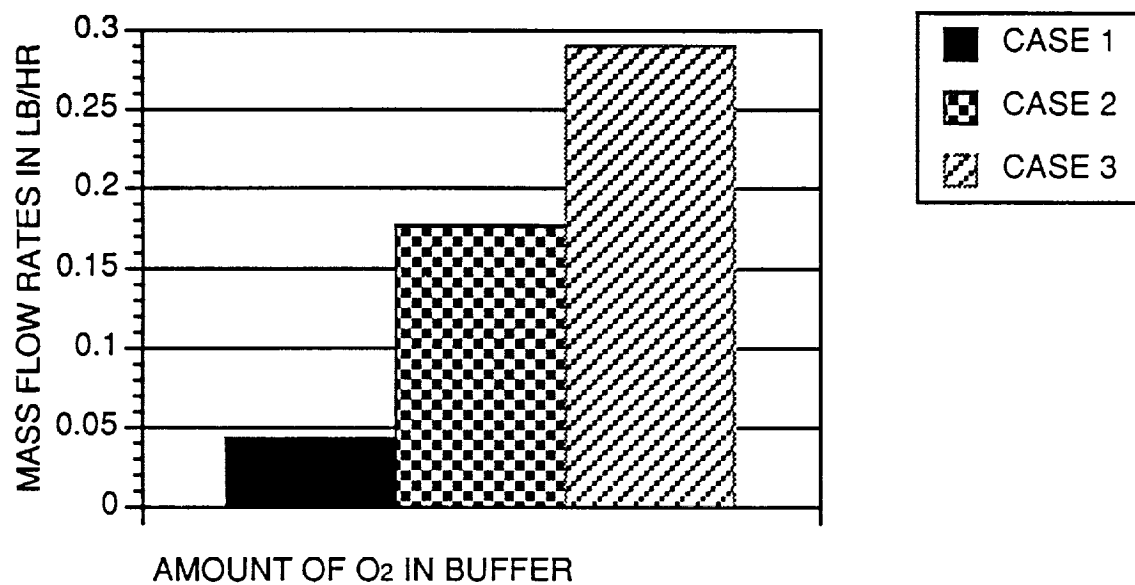


Figure 26B: Overall effect on the oxygen buffer for different crew scenarios

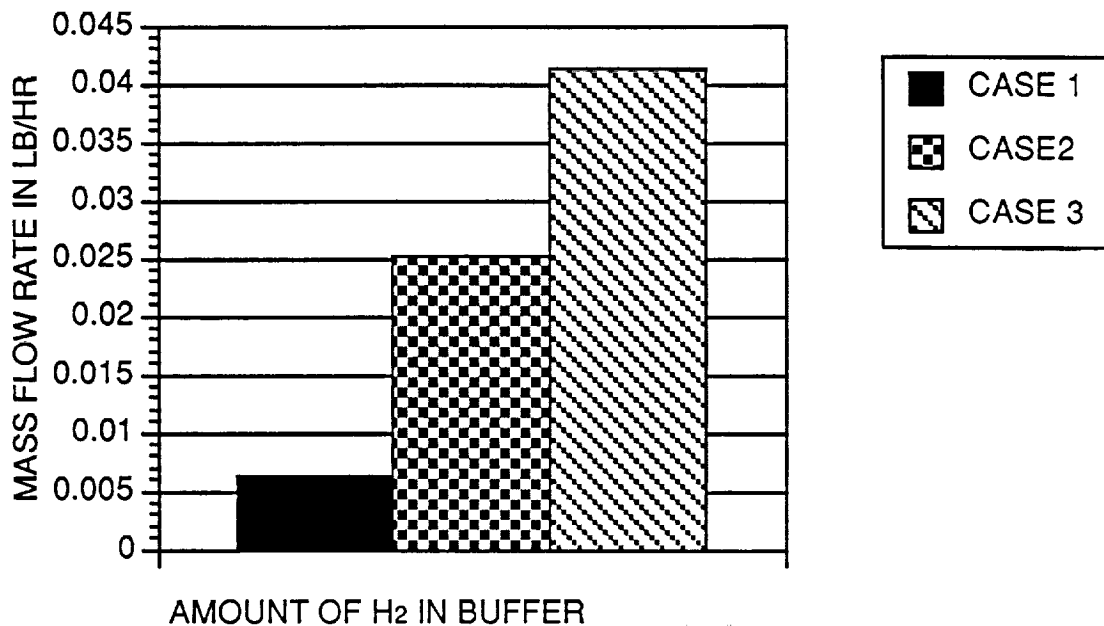


Figure 26C: Overall effect on the hydrogen buffer for different crew scenarios

Comparing Figures 26A, 26B and 26C we see that as the food consumption increases, the amount of  $O_2$  and  $H_2$  in the buffer increases. This is in accordance with the basic mass conservation law for a steady state system i.e the excess oxygen and hydrogen atoms which enter the system in the form of food eventually leave the system as gases which are then stored in the buffer.

#### Technology trade study

As outlined in chapter 4 each ECLSS subsystem can be modeled by a wide variety of candidate technologies. In order to choose the appropriate technology for the ECLSS configuration desired apart from knowing the subsystem efficiency, it is also essential to know how the introduction of the system affects the rest of the LSS.

Figures 27 and 28 show the comparison between competing technologies for water regeneration and CO<sub>2</sub> reduction respectively.

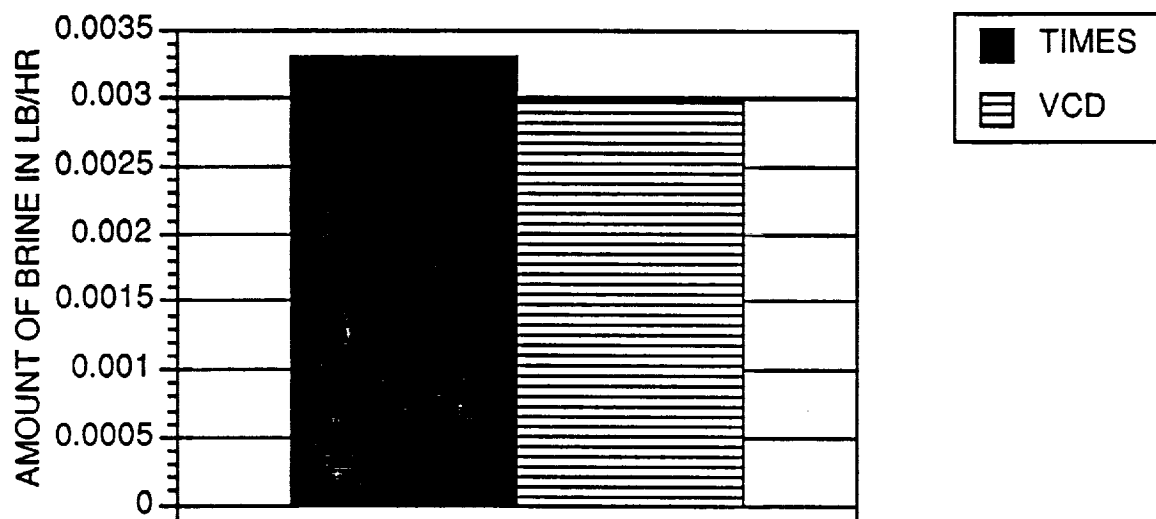


Figure 27A : Mass flow rates of brine from the VCD and TIMES.

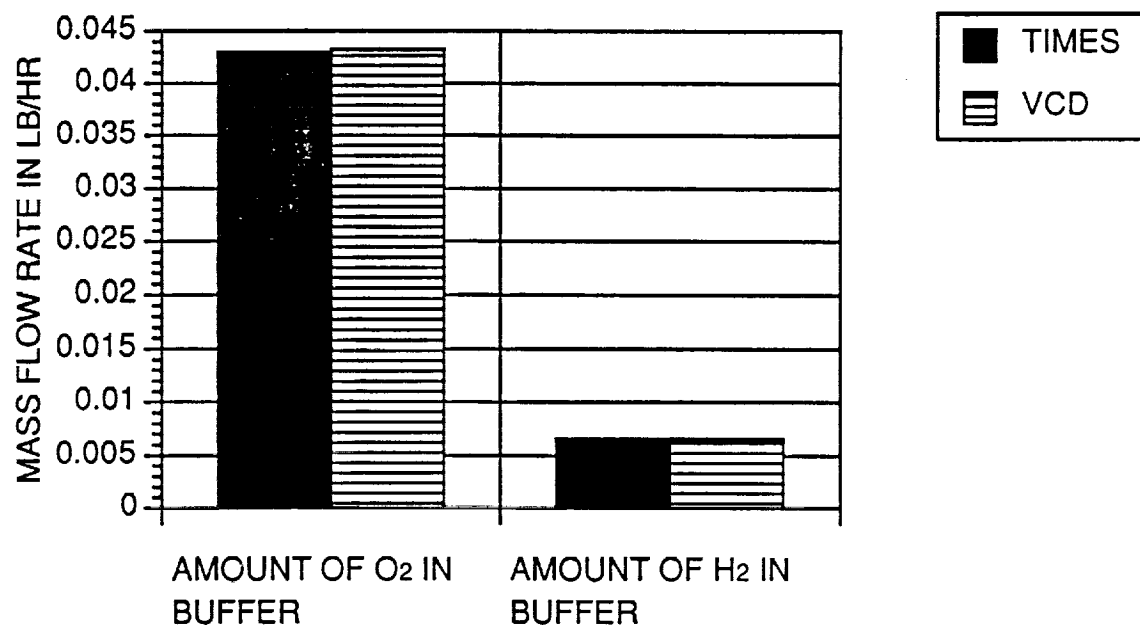


Figure 27B: Effect of VCD and TIMES on the overall system.

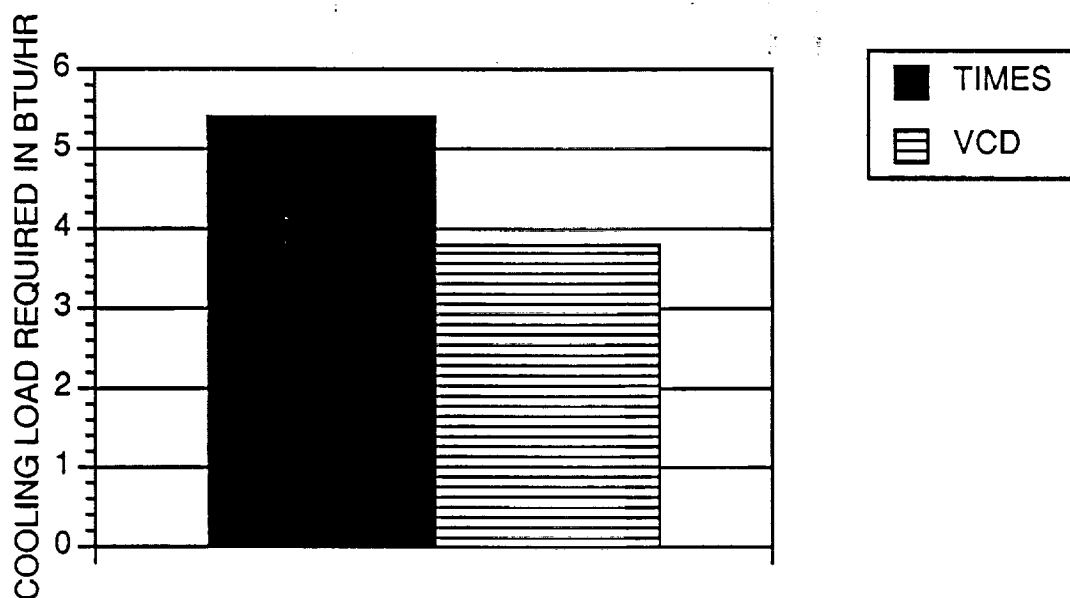


Figure 27 C: Comparison of cooling load required for the VCD and TIMES.

From Figures 27A, 27B, and 27C, we can deduce that VCD is more advantageous than TIMES, as:

- The cooling load required for VCD is lower than that required for TIMES. This is in accordance with the values reported in literature, which says that the TIMES requires twice the energy per pound of water produced compared to the VCD due to the inherent inefficiencies of the process, (Schubert,1983).
- More  $O_2$  and  $H_2$  is stored in the buffer when a VCD is used.
- Recovery efficiency of the VCD is greater than that of the TIMES. This is in agreement with the reported values of 96% recovery for the VCD and 92% for the TIMES, (Schubert,1983). The simulation values reported are however higher than the experimentally calculated values. This can be explained because for our simulation purpose we have assumed a steady state continuous process.

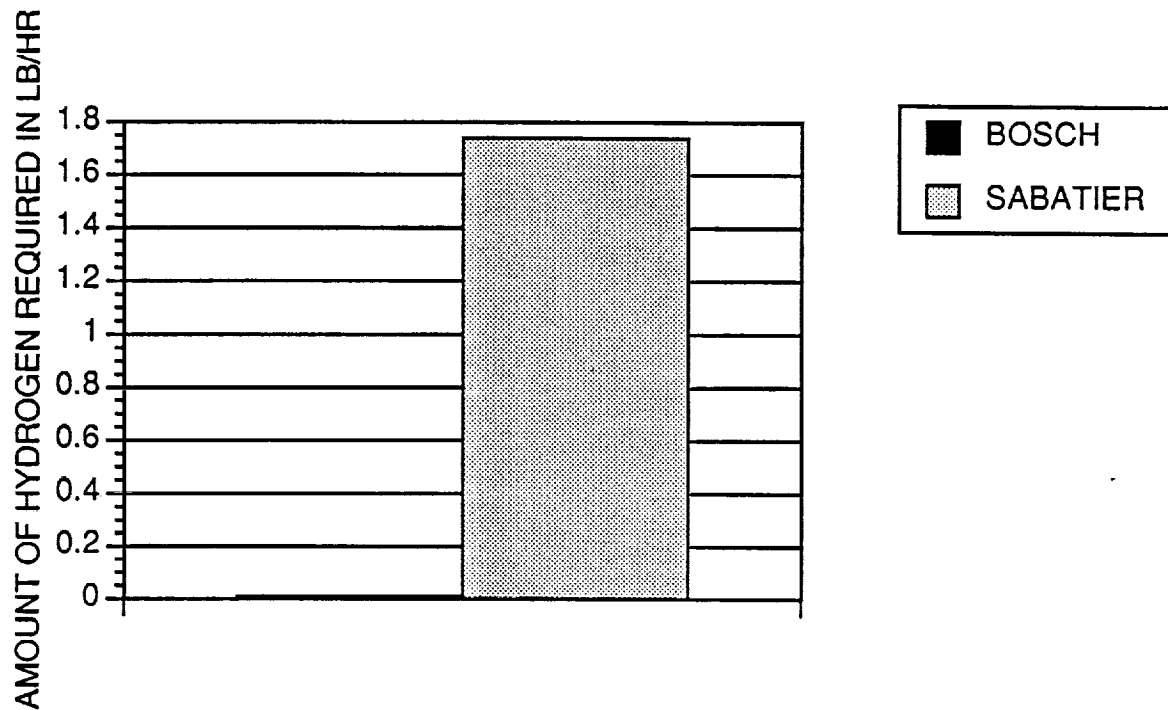
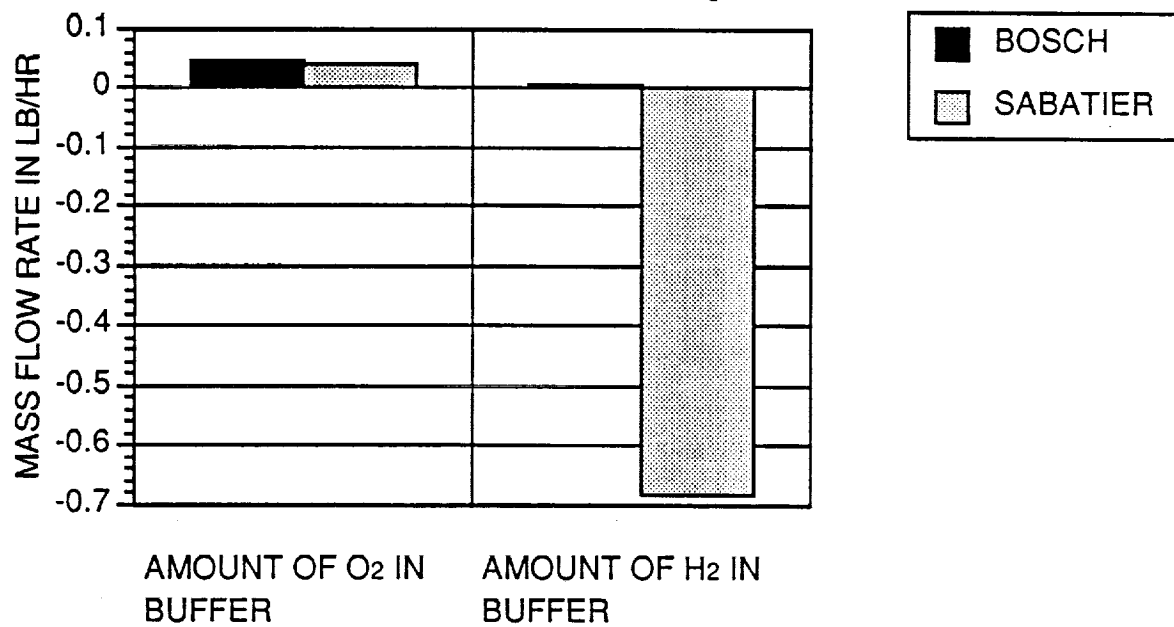


Figure 28A : Comparison of H<sub>2</sub> feed flow rate required for Bosch and Sabatier



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Figure 28B : Comparison of the overall effect on the entire system due to the presence of the Bosch or the Sabatier.

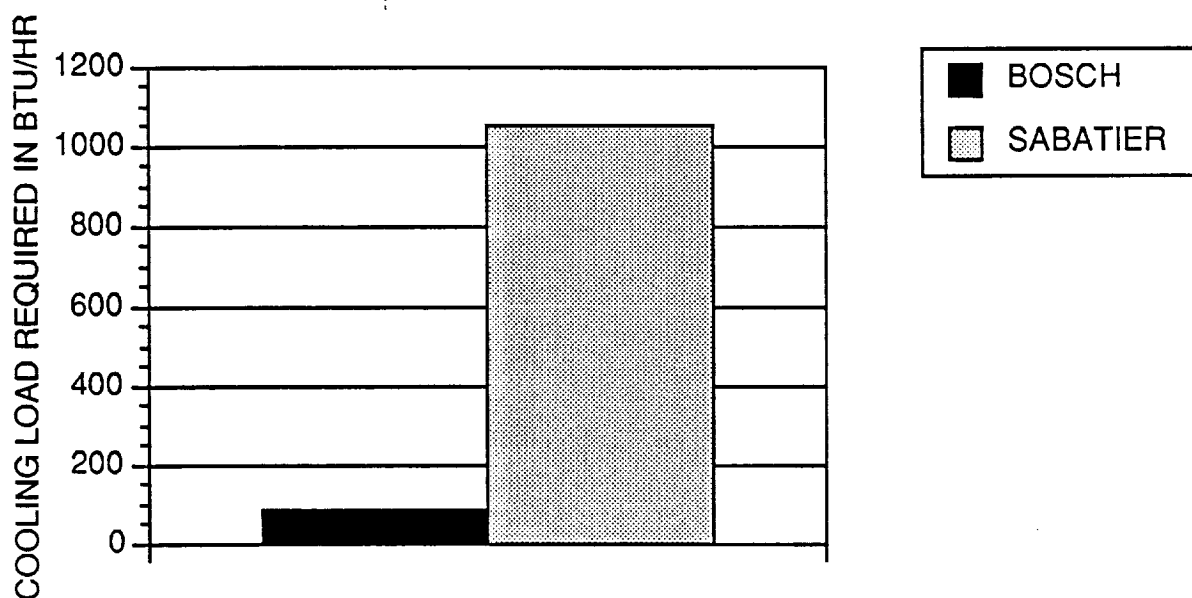


Figure 28C : Comparison of cooling load required for the Bosch and Sabatier

Similar to our deductions for VCD and TIMES from Figures 28A, 28B and 28C we can draw the analogy that the Bosch process is more advantageous as compared to the Sabatier process. This is substantiated by :

- The amount of  $H_2$  required for the Sabatier being greater than the Bosch a continuous supply of  $H_2$  is required to be supplied to the system for the operation of the Sabatier reactor. This is in agreement with the stoichiometric relation of the reactions taking place in the two reactors respectively.
- The amount of  $O_2$  and  $H_2$  stored in the buffer is greater when a Bosch reactor is used in place of a Sabatier reactor.
- The overall cooling load required is less for a Bosch as compared to a Sabatier.

This is in apparent contradiction to the reported values in literature where the power requirement for a Bosch is 1.1 times that for the Sabatier, (Spina and Lee, 1985). This can be explained by considering that the amount of  $CO_2$  to be treated for the basal case for the Bosch and Sabatier is 0.0465 and 0.4327 lb/hr respectively. This is so

because all the  $\text{CH}_4$  formed in the Sabatier is oxidized in the Trace removal subsystem which adds an additional load to the  $\text{CO}_2$  reduction subsystem.

#### Parameter sensitivity

The developed integrated model of the ECLSS can be used to study the performance criterion of the ECLSS functional units. Figure 29 shows the variation in performance of the Bosch reactor and its overall effect on the entire ECLSS as the mass ratio of the bleed stream from the Bosch to the Trace Removal system is varied from 0 to 1.0 as shown in the three cases, where :

Case 1 : Bleed fraction is 0.0

Case 2 : Bleed fraction is 0.5

Case 3 : Bleed fraction is 1.0

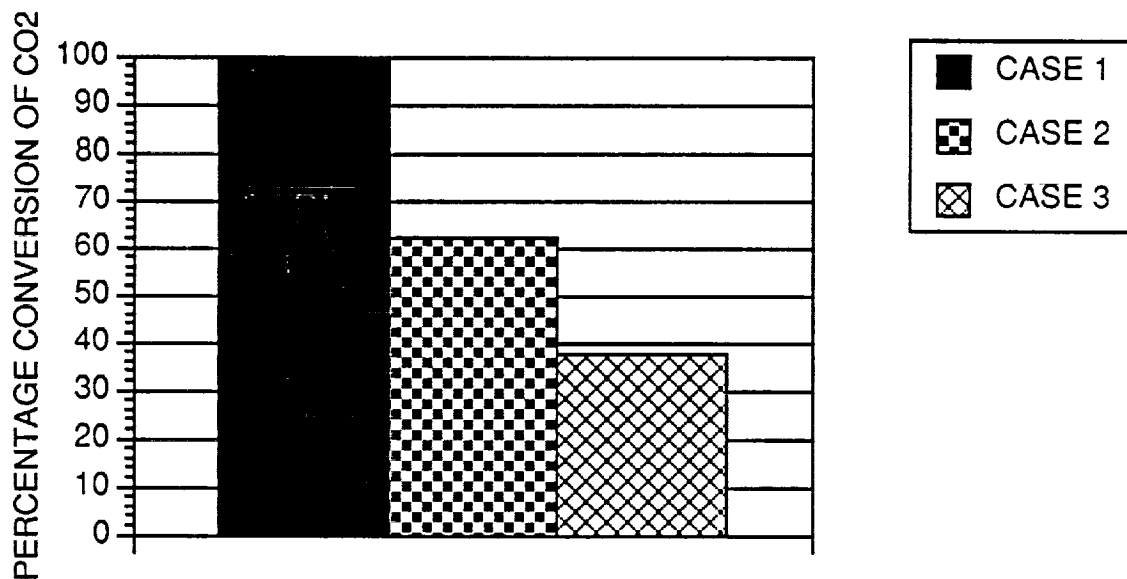


Figure 29A: Comparison of efficiency for different bleed fractions.



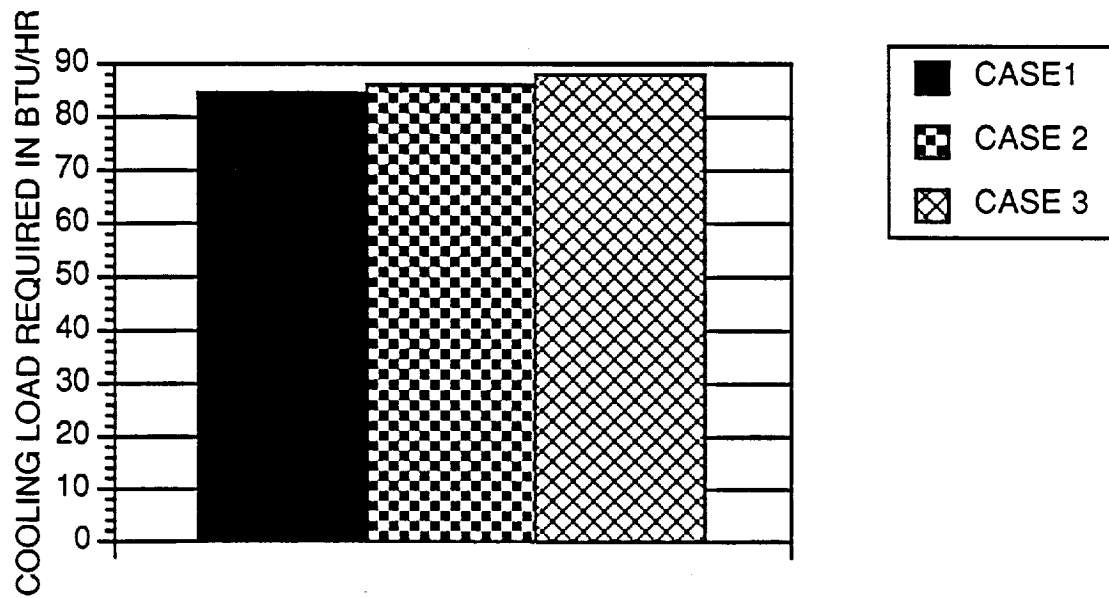


Figure 29B : Comparison of cooling loads for different bleed fractions

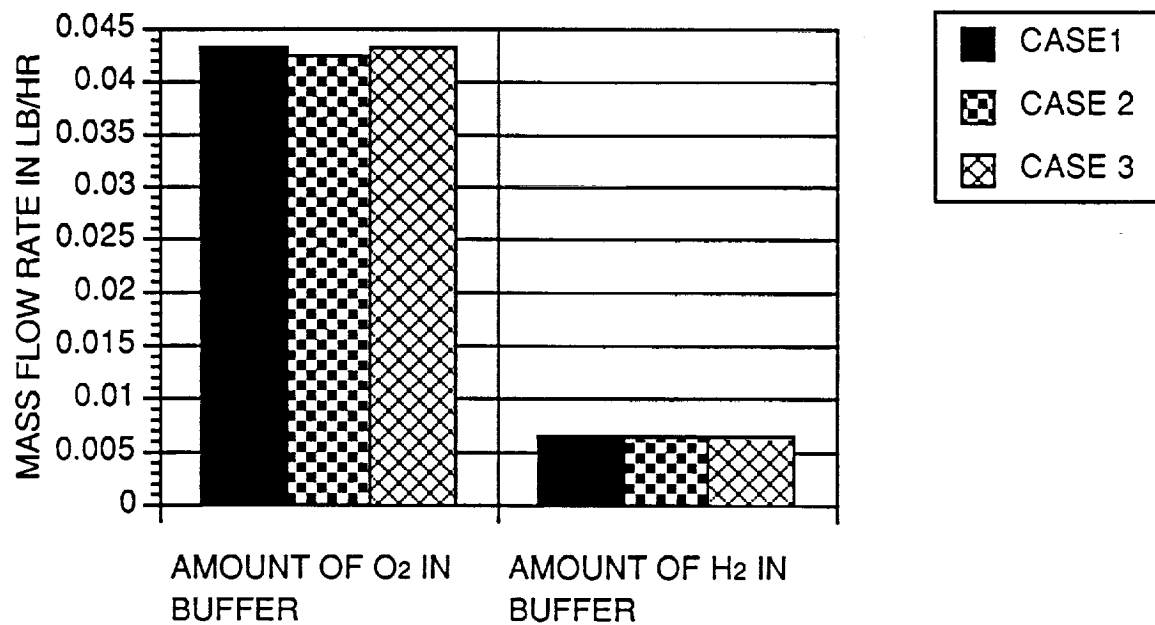


Figure 29C : Overall effect on the system for the different bleed fractions adopted

The result shown in Figure 29A is in accordance with the values reported in literature (Spina and Lee,1985). The single pass efficiency for a Bosch reactor using iron catalysts is reported to be less than 10%. The value calculated from our model (bleed fraction equal to 1.0) is 37.6%. This discrepancy could be explained by the over estimation in our model where Gibbs equilibrium is assumed to be attained in both the reactors. This does not occur under actual operating conditions, as mentioned earlier in chapter 4. With the total recycle, (bleed fraction equal to 0.0) conversion of 99.6% is attained which is again in accordance with Lee's results, (Spina and Lee,1985).

The integrated ECLSS model can also be used to study the effect of varying the cabin conditions on the overall system. The result of our analysis can be used to determine an optimum between cabin conditions and amount of expendables to be supplied or stored. Two sample cases are observed for different environment specifications in the cabin. Both the cases are for one man operating at basal metabolic rate. The situations are as:

Table 4: Different scenarios for cabin environment

Mole fraction of gases in the cabin	Case 1	Case 2
Oxygen	0.208	0.160
Nitrogen	0.769	0.769
Water vapor	0.02	0.068
Carbon dioxide	0.003	0.003

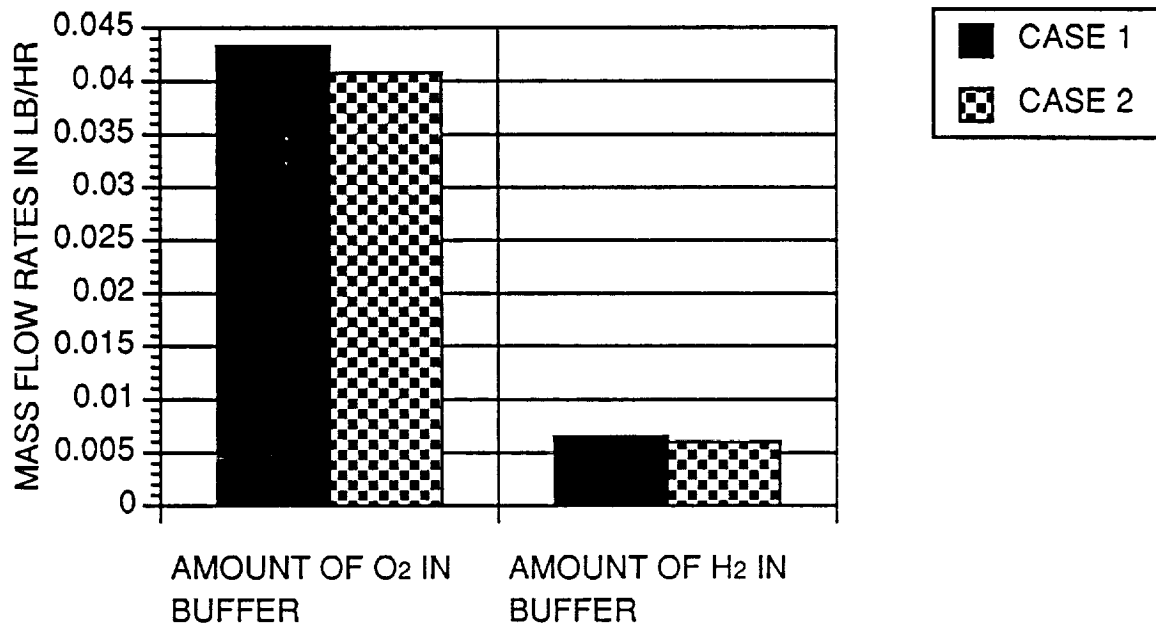


Figure 30: Comparison of the effect on the overall LSS for different cabin environments.

As shown in Figure 30 Case 1 is optimum compared to Case 2 as more O<sub>2</sub> and H<sub>2</sub> is stored in the buffer. This shows that the optimum cabin requirement is Case 1 which is same as the standard requirements for the cabin, (Humphries et al, 1986)

## 6 THERMODYNAMIC ANALYSIS OF THE CLOSED LOOP LIFE SUPPORT SYSTEM

The goal of any energy conservation study is to establish the minimum amount of energy necessary to operate a certain process. In the study which was carried out, (Brandhorst, 1991) the per capita power consumption for a partially closed and completely closed regenerable life support system were estimated as 3.5 kw/individual and 10 - 12 kw/individual respectively.

The objective of this chapter is to present an estimate of an alternative energy efficiency of the various sub units comprising the closed loop life support system calculated on the basis of the second law of thermodynamics.

### Why second law?

In designing different LSS modules scientists usually consider the efficiency of the equipment based on the first law of thermodynamics. It has been shown in general that the average first law efficiency of most process is about 50%, (Cook, 1971).

However in a long term application we may be faced with the problem of **entropy crisis**. A system is using energy sources of low entropy probably solar and releasing energy of higher entropy. This is of concern to us because our goal should be to keep the net entropy production of a system as low as possible, and still ensure a positive entropy gradient between the system and the surroundings. As the net entropy production of a system increases, the entropy gradient between the system and the surrounding decreases and the system will gradually approach equilibrium with the surroundings until reaching the point where the entropy gradient is equal to zero. At this point no work can be extracted from the system. A measure of this

entropy generation can be obtained by evaluating the second law efficiency of the process.

From another perspective, from literature, the second law efficiency of a process is usually about 10%, (Reistad,1980). This indicates that 90% of the available work is usually lost in irreversibilities. Thus, the second law efficiency indicates that there is a great margin for improvement in the design of equipments auguring well for further large and rapid increases in efficiency.

#### Methodologies available for the second law analysis

The lowest energy we use can be derived from the application of the second law of thermodynamics. Quantities such as the available energy may be used to describe the irreversibilities of the process, ( Denbigh, 1957). There are two widely used methods to study the process irreversibilities. They are :

- **Availibility analysis /Exergy analysis.**
- **Lost work analysis.**

We shall now dwell briefly upon the steps followed for each of the above methodologies.

#### Availability Analysis

The technique of Availability Analysis was first proposed by Guoy and Stodola (Guoy, 1889 and Stodola 1898). Over the past years Availability Analysis has been extensively used in ares ranging from space heating to cryogenic processes, (Herbert and Stephen 1980, Ahern ,1980 (a)).

Many processes ocur in an atmosphere which for all practical purposes is an inexhaustible source (or sink). The process is usually occuring because the system is not in thermal, mechanical or chemical equillibrium with the surroundings. The tendency of any natural process is to come to equilibrium with the surroundings.

This equilibrium state is known as the "dead state", (Moran,1982). In the dead state there is no spontaneous change occurring within the system or the environment, or no spontaneous interaction between the two.

As the system moves towards its dead state it expends energy. Maximum work can be extracted if the system under study undergoes a totally reversible process in coming to its dead state. This maximum work is called as "available work". For an open system where there is inflow and outflow of mass, the available energy associated with mass inflow is termed as "exergy", (Moran, 1982).

The following general equation has been proposed to calculate the exergy at a point in the system (Ahern, 1980)

$$\begin{aligned} \text{Exergy} = (U - U_0) - T_0 (S - S_0) + \frac{p_0}{J}(v - v_0) + \frac{v^2}{2gJ} + (z - \\ z_0)\frac{g}{gcJ} + \sum_c (\mu_c - \mu_0)W_c + E_i A_i F_i (3T^4 - T_0^4 - \\ 4T_0 T_3) + \dots \end{aligned} \quad (32)$$

where :

$(U - U_0)$  is the internal energy

$T_0 (S - S_0)$  is the entropy

$\frac{p_0}{J}(v - v_0)$  is the work

$\frac{v^2}{2gJ}$  is the momentum

$(z - z_0)\frac{g}{gcJ}$  is work done against gravity

$\sum_c (\mu_c - \mu_0)W_c$  is the chemical work

$E_i A_i F_i (3T^4 - T_0^4 - 4T_0 T_3)$  is radiation emission

the subscript 0 indicates the reference state or the environment

The thermodynamic efficiency based on exergetic analysis may be defined as, (Chiu and Newton, 1980)

$$\text{Thermodynamic efficiency} = \frac{\text{exergy in product}}{\text{exergy supplied to the system}} \quad (33)$$

### Lost Work Analysis

The method of lost work analysis was first proposed by Seader, (Nevers and Seader, 1980).

The basic requirement of the second law is :

The total entropy change of an isolated system,

$$\Delta S_{\text{sys}} \geq 0.0 \quad (34)$$

For a control volume with a steady state process where the surroundings are at a temperature of  $T_0$ , the total entropy change of the system is given by, (Smith and Van Ness 1987)

The rate of change of total entropy of the system = Net rate of entropy transfer by flowing streams + Rate of entropy exchange with the surroundings

Thus

$$\Delta(Sm)_{fs} - \frac{Q}{T_0} > 0.0 \quad (35)$$

where  $\Delta(Sm)_{fs}$  is the difference in entropy between the feed and the product

$Q$  is the net heat transfer from the system to the surroundings

For a steady state flow process there is no internal energy accumulation within the system. The law of conservation of energy can be expressed as ,

$$\Delta \left[ \left( H + \frac{1}{2} u^2 + zg \right) \right]_{fs} = Q - W_s \quad (36)$$

where  $\Delta \left[ \left( H + \frac{1}{2} u^2 + zg \right) \right]_{fs}$  is the difference in energy between the in flow and the outflow streams.

$Q$  is the heat flow into the system

$W_s$  is the work done by the system

For any system which requires work the amount of work required will be a minimum if the system undergoes a reversible change. This minimum work required is called the "ideal work", ( $W_{ideal}$ ). Since there is no degradation of work the entropy generation for a reversible process is equal to zero and equation (35) becomes

$$Q = T_0 \Delta(Sm)_{fs}$$

Substituting the above value in equation (36) and rearranging gives

$$W_{ideal} = T_0 \Delta(Sm)_{fs} - \Delta \left[ \left( H + \frac{1}{2} u^2 + zg \right) \right]_{fs} \quad (37)$$

In most processes the kinetic and potential energy terms are negligible, and equation (37) can be written as

$$W_{ideal} = T_0 \Delta(Sm)_{fs} - (\Delta H)_{fs} \quad (38)$$

It is justified to mention here that from an availability viewpoint, according to the definition of  $W_{ideal}$  as given in (38), the minimum work required is equivalent to the difference in availability between the input and the output streams.

For a work producing process the "lost work" is the work which is lost due to irreversibilities within the process. It is expressed as the difference between the ideal work which could be produced by the process ( $W_{ideal}$ ) and the actual work



produced by the process ( $W_s$ ). Thus from equations (36) and (38),  $W_{lost}$  can be written as

$$W_{lost} = T_0 \Delta(Sm)_{fs} - Q \quad (39)$$

Conventionally, there are two kinds of processes. A spontaneous process is one which produces work, i.e.  $W_{ideal}$  is positive. Then

$$W_s = W_{ideal} - W_{lost} \quad (40)$$

A nonspontaneous process is one which requires some form of external work to be supplied, i.e.  $W_{ideal}$  is negative. Hence

$$|W_s| = |W_{ideal}| + W_{lost} \quad (41)$$

Thereby the second law efficiency for each type of process can be defined as

$$\eta_2 (\text{spontaneous process}) = \frac{W_s}{W_{ideal}} \quad (42)$$

$$\eta_2 (\text{nonspontaneous process}) = \frac{W_{ideal}}{W_s} \quad (43)$$

For our analysis we used the Lost Work analysis method. The reasons for doing so are enumerated below

- Calculation of lost work gives us a more intuitive insight into the energy loss within the process.
- For a process where the goal is to produce a stream having high availability, the calculation of a availability loss in the output stream makes no sense. However in the lost work approach we are only concerned with the irreversibilities within the process.

#### Method of Approach

The technique adopted to calculate the thermodynamic efficiency of the ECLSS is:

- (1) The process boundary is defined.

(2) Consistent heat and material balance data is obtained. This data is obtained from our ASPEN model of the ECLSS.

(3) Selection of ambient temperature as a reference. We choose the cabin temperature of 70° F.

(4) Evaluating the  $W_{lost}$  within each functional unit of the ECLSS subsystem.

(5) Calculating the  $W_{ideal}$  for each subsystem based on the subsystem information.

(6) Knowing the  $W_{lost}$  and  $W_{ideal}$  the second law efficiency of each subsystem is evaluated.

### Results

The advantage of the lost work analysis was demonstrated by applying this technique to a few ECLSS sample technologies. The stream information like enthalpy, entropy, and mass flow rates were obtained from our integrated ASPEN model. The values are obtained for a basal case of a crew of 1 man of 25 years of age weighing 60 kg operating at basal metabolic rate.

### Wet Oxidation of Solid Waste

Refer Figure 24 for stream identification.

Table 5: Properties of streams involved in wet oxidation process.

St Stream	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr ° R)
S1	$3.44 \times 10^{-4}$	$12.91 \times 10^{-4}$	$23.56 \times 10^{-7}$
S2	$9.16 \times 10^{-4}$	$-1.4 \times 10^{-3}$	$-2.64 \times 10^{-3}$
S3	$1.26 \times 10^{-3}$	-4.77	$-3.63 \times 10^{-6}$
S4	$1.26 \times 10^{-3}$	-4.85	$1.72 \times 10^{-5}$
S5	0.0	0.0	
Q1	Heat Duty =	-4.77 Btu/hr	
Q2	Heat Duty=	-0.08 Btu/hr	

The lost work analysis of each unit operation block comprising the solid waste oxidizer is given in Table 6.

Table 6: Lost work estimation of the solid waste oxidizer

Unit Operation block	Lost work (Btu/hr)	% of total lost work
Wet oxidizer	4.71	98.1
Depressurizer	0.091	1.9
Total lost work	4.801	

$$W_{\text{ideal}} = 530 (1.72 \times 10^{-5} + 2.64 \times 10^{-3} - 23.56 \times 10^{-7}) - (-4.85 -$$

$$12.91 \times 10^{-4} + 14.05 \times 10^{-4})$$

$$= 6.26 \quad \text{Btu/hr}$$

W<sub>ideal</sub> being positive this is a spontaneous process. Hence

$$W_s = 6.26 - 4.801$$

$$= 1.459$$

$$\eta_2 = \frac{1.459}{6.26}$$

$$= 23.3\%$$

### Catalytic Oxidation of Trace Contaminant Gases:

Refer Figure 15 for stream identification.

Table 7: Stream properties of Catalytic oxidation subsystem

Stream	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr ° R)
S1	35.66	-3291.38	1.17
S2	3.45	-318.44	0.113
S3	3.45	135.9	0.71
S4	3.45	309.64	0.86
S5	3.45	309.33	0.86
S6	3.45	-145.0	0.39
S7	32.21	-2972.98	1.05
S8	32.21	-2975.56	1.05
S9	35.66	-3120.25	1.49
Q1	Heat duty =	173.7	(Btu/hr)
Q2	Heat duty =	-0.297	(Btu/hr)
Q3	Heat duty =	-2.56	(Btu/hr)

The lost work analysis of each unit operation block comprising the Catalytic Oxidizer is shown in Table 8.

Table 8: Lost work estimation of Catalytic oxidation subsystem

Unit operation block	Lost work (Btu/hr)	% of total lost work
Diverter	0.0	0.0
Heat exchanger	67.31	38.2
Heater	79.5	45.1
HTCO	0.297	0.17
LTCO	2.56	1.45
Mixer	26.5	15.04
Total lost work	176.17	

$$\begin{aligned} W_{\text{ideal}} &= 530 (1.49 - 1.17) - (-3120.25 + 3291.38) \\ &= -1.53 \text{ Btu/hr} \end{aligned}$$

This is a non spontaneous process. Hence

$$\begin{aligned} W_s &= 1.53 + 176.17 \\ &= 177.7 \text{ Btu/hr} \\ \eta_2 &= \frac{1.53}{177.7} \\ &= 0.86\% \end{aligned}$$

#### Bosch subsystem

Refer Figure 19 for stream identification. The bleed stream fraction is assumed to be zero.

Table 9: Stream properties of Bosch subsystem

Stream	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr °R)
S1	0.048	-183.79	$-6.04 \times 10^{-4}$
S2	$4.37 \times 10^{-3}$	$-54.16 \times 10^{-6}$	$-5.98 \times 10^{-7}$
S3	0 0.398	-677.1	-0.139
S4	0.398	515.04	0.778
S5(solid)	$1.3 \times 10^{-2}$	4.51	$4.27 \times 10^{-3}$
S5(vapor)	0.385	-130.4	0.436
S6	$3.9 \times 10^{-2}$	-268.11	-0.087
S7(solid)	$1.3 \times 10^{-2}$	-0.08	$-1.5 \times 10^{-4}$
S7(vapor)	0.346	-507.11	-0.177
S8	$1.3 \times 10^{-2}$	-0.015	$-2.87 \times 10^{-5}$
S9	0.398	-677.1	-0.139
Q1	Heat duty =	1192.14	Btu/hr
Q2	Heat duty =	-640.93	Btu/hr
Q3	Heat duty =	-649.41	Btu/hr

Table 10 indicates the amount of lost work in each functional unit comprising the Bosch subsystem.

Table 10: Lost work analysis of unit operation blocks of Bosch subsystem

Unit operation block	Lost work (Btu/hr)	% lost work
Mixer	6.89	0.55
Reactor 1	486.01	39.04
Reactor 2	461.95	37.11
Condensate remover	276.13	22.18
Solid carbon remover	13.78	1.11
Total lost work	1244.76	

$$\begin{aligned}
 -W_{\text{ideal}} &= 530 (-2.87 \times 10^{-5} - 0.087 + 6.21 \times 10^{-4} + 5.98 \times 10^{-7} - 1.72 \times 10^{-5}) - \\
 &\quad (-286.11 - 0.015 + 178.94 + 54.16 \times 10^{-6} + 4.85) \\
 &= 38.53 \quad \text{Btu/hr}
 \end{aligned}$$

Hence this is a spontaneous process.

$$\begin{aligned}
 W_s &= 38.53 - 1244.76 \\
 &= -1206.23
 \end{aligned}$$

This is an example of a highly non ideal process. The actual process is spontaneous however under simulated working conditions the process requires external work to be supplied.

#### Static Feed Water Electrolysis

Refer Figure 23 for stream identification.

Table 11 : Properties of streams present in the Water Electrolysis Subsystem.

Stream	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr ° R)
S1	$9.6 \times 10^{-2}$	-654.8	-0.21
S2	$9.6 \times 10^{-2}$	-654.83	-0.21
S3	$9.6 \times 10^{-2}$	-654.83	-0.21
S4	$9.6 \times 10^{-2}$	-0.38	-0.27
S5	$1.07 \times 10^{-2}$	-0.25	$-4.76 \times 10^{-4}$
S6	$8.52 \times 10^{-2}$	-0.13	$-2.46 \times 10^{-4}$
Q1	Heat duty =	-0.03 Btu/hr	
Q2	Heat duty =	654.55 Btu/hr	

Table 12: Lost work analysis within the Water Electrolysis Subsystem

Unit operation block	Lost work (Btu/hr)	% lost work
Pump	0.427	0.38
Cooler	0.03	0.03
Electrolyzer	96.99	87.08
Gas separator	13.93	12.51
Total lost work	111.38	



$$\begin{aligned}
 W_{ideal} &= 530 (-4.76 \times 10^{-4} - 2.46 \times 10^{-4} + 0.21) - (-0.13 - 0.25 + 654.8) \\
 &= -543.5 \text{ Btu/hr}
 \end{aligned}$$

$W_{ideal}$  being negative, this is a spontaneous process.

$$\begin{aligned}
 W_s &= -654.88 \text{ Btu/hr} \\
 \eta_2 &= \frac{543.5}{654.88} \\
 &= 82.99\%
 \end{aligned}$$

### Humidity Condensate Removal

Refer Figure 16 for stream identification.

Table 13: Stream properties of streams occurring in Humidity Condensate Remover

Stream	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr ° R)
S1	35.66	-3120.22	1.49
S2	$7.18 \times 10^{-2}$	-489.58	-0.154
S3	35.59	-2783.35	1.35
Q1	Heat duty =	-152.71	Btu/hr

Since the heat of condensation is not being used to do any useful work, hence,

$$\begin{aligned}
 \text{Lost work} &= 530 (1.35 + 0.154 - 1.49) + 152.71 \\
 &= 160.13 \text{ Btu/hr}
 \end{aligned}$$

$$\begin{aligned}
 W_{ideal} &= 530 (1.35 + 0.154 - 1.49) - (-489.58 - 2783.35 + 3120.22) \\
 &= 160.13 \text{ Btu/hr}
 \end{aligned}$$

$$W_s = 0$$

$$\text{Thus } \eta_2 = 0$$

This is valid since we had assumed that the heat of condensation is not used for doing useful work, thereby the amount of work which can be obtained from the process is zero.

## 7 CONCLUSIONS AND RECOMMENDATIONS

We arrive at the following conclusions from the first part of this project :

The integrated Environmental Control and Life Support System (EELS) model can be used to assess the parameter requirements for different space station conditions. The utility of a particular configuration is judged on the basis of the amount of oxygen and hydrogen stored in their respective buffers and the heating/cooling load required. The excess oxygen and hydrogen is stored as a reserve for cases of exigency for example to provide oxygen to the cabin if there occurs a failure in the oxygen generation unit. However the oxygen and hydrogen stored in the buffer will bear an impact on the load carrying capability of the space shuttle. This has not been explored in our present model.

Recommended future work in this area is :

- To develop a more rigorous model of the various EELS components like the water electrolysis system and the CO<sub>2</sub> membrane removal system.
- To develop a rigorous dynamic biological model of the crew.
- To develop a dynamic model of the entire ECLSS using the values obtained from our steady state model as the initial values.

The latter part of this project was concerned with the 'lost work' analysis. An analysis of lost work at the subsystem component level enables the designer to identify principal sources of entropy generation and strive to minimize them. Thus the overall conclusion to be drawn from this work is that there exists a potential for energy conservation in the currently used ECLSS technologies which warrants evaluation of the present operating conditions. In order to arrive at a detailed

optimum design of the ECLSS subsystem it is recommended to evaluate the lost work for every hardware component constituting the subsystem which would enable the designer to exactly pin point the areas of maximum entropy generation.

## BIBLIOGRAPHY

- Ahern, J.E., (a), 1980, Applications of the Second Law of thermodynamics to Cryogenics - A Review, *Energy*, 5, pp 891- 898.
- Ahern, J.E., 1980, *The Exergy Method of Energy Systems Analysis*, John - Wiley & Sons, New York.
- Ammann, K., 1989, Development of the Catalytic Oxidizer Technology for the European Space Program, Paper No 891533, Ninetenth Intersociety Conference on Environmental Systems, San Diego, California.
- ASPEN PLUS User Guide, August 1988, Aspen Technology Inc, Cambridge, Massachusetts.
- Bangham, M.E., and Reuter, J.L., 1987, A Computer Aided Engineering tool for ECLS systems, Paper No 871423, Seventeenth Intersociety Conference on Environmental systems, Seattle, California.
- Barker, R.S., Blakely, R.L., Hamill, T.D., and Nicol, S.W., September 1971, G189A, Generalized Environmental/Thermal Control and Life Support Systems Computer Program - Program Mannual, Mc Donnell Douglas Corporation Report, MDAC GZ44.
- Brandhorst, Jr., H.W., 1991, Energy Requirements for the Space Frontier, Paper No 912064, Twentyfirst Intersociety Conference on Environmental Systems, San Francisco, California.
- Bursztein, S., Elwyn, D.H., Askanazi, J., and Kinney, J.M., 1989, *Energy Metabolism, Indirect Calorimetry, and Nutrition*, Williams and Wilkins, Maryland, pp 27-85.
- Chiu, C.H., and Newton, C.L., 1980, Second Law Analysis in Cryogenic

- Processes, Energy 5, pp 899-904.
- Cook,E., 1971, ,Sci Am, 225.
- Denbigh,K., 1957, The Principles of Chemical Equilibrium, Cambridge University, MA.
- Fleisch,A., 1951, Le Metabolisme basal standard et sa determination au maydem du " Metabocalculator ", Helv. Med. Acta, 18, pp 23-44.
- Fortunato,F.,A., et al, 1988, Static Feed Water Electrolysis System for Space Station Oxygen and Hydrogen Generation, Paper No 880994, Eighteenth Intersociety Conference on Environmental Systems, San Francisco, California.
- Garmirian,J.,E., Manning,M.,P., and Reid,R.,C., 1980, The Use of Nickel and Cobalt Catalysts in a Bosch Reactor, Paper No 80-ENAS-15, Intersociety Conference on Environmental Systems, San Diego, California.
- Guoy,G., 1889, J.physique,8.
- Gustavino,S.,R., Mankamyer,M.,M., 1989, Applications of Bioregenerative Subsystems to an Environmental Control and Life Support System for a manned Mars Sprint mission, Paper No 891504, Nineteenth Intersociety Conference on Environmental Systems, San Diego, California.
- Haines,R.,W., 1988, HVAC Systems Design Handbook, TAB Books Inc., Blue Ridge Summit, PA, pp 9-54.
- Hall,Jr., J.,B., December 6, 1990, Space Station Freedom Environmental Control and Life Support System (ECLSS) Development Status, Presented to the Space Systems and Technology Advisory Committee, AdHoc Review Team Advanced Life Support Technology.
- Herbert,W.,H., and Stephen,C.,H., 1980, Second Law Analysis : An Alternative Indicator of System Efficiency, Energy 5, pp 865 - 874.

- Holmes, R., F., King, C., D., and Keller, E., E., January 1973, Bosch CO<sub>2</sub> Reduction System Development, Interim Report, GDCA - DBD73 - 0001, Contract NAS8-27276, Convair Division of General Dynamics, San Diego, California.
- Humphries, W., R., et al., 1986, Space Station Environmental Control and Life Support System Distribution and Loop Closure Studies, Paper No 860942, Sixteenth Intersociety Conference Environmental Systems, Detroit, Michigan.
- Huttenbach, R., C., and Radford, J., H., 1989, Life Support - Future Trends and Developments, Paper No 891549, Nineteenth Intersociety Conference on Environmental Systems, San Diego, California.
- King, D., D., and Holmes, R., F., July 1976, A Mature Bosch CO<sub>2</sub> Reduction Technology, Paper No 76-ENAs- 14, Intersociety Conference on Environmental Systems, San Diego, California.
- Kolodney, M., Lange, K., E., and Edeen, M., A., 1991, Modelling of Advanced ECLSS/ARS with ASPEN, Paper No 911506, Twentyfirst Intersociety Conference on Environmental Systems, San Diego, California.
- Lehinger, A., L., 1977, Biochemistry, 2nd ed, Worth Publishers Inc, New York.
- Likens, W., and Force, E., 1988, Simulation Software Evaluation Report, prepared by NASA Ames Research Center.
- LiSSA, 1992, NASA/JPL Life Support Systems Analysis Simulation Tool.
- Lockheed Missiles & Space Company, Inc., Development of a preprototype Vapor Compression Distillation water recovery subsystem, Report for Contract, NAS 9-15136.
- Lusk, G., 1928, The Elements of the Science of Nutrition, 4th ed, W.B. Saunders Company, Philadelphia, pp 400-446.
- Manning, M., P., and Reid, R., C., 1975, CO<sub>2</sub> Reduction by the Bosch Process, Paper

- No 75-ENAs-22, Intersociety Conference on Environmental Systems, San Francisco, California.
- Manning, M.P., Reid, R.C., and Sophonpanich, C., July 1982, Carbon Deposition in the Bosch Process with Ruthenium and Ruthenium-Iron Alloy Catalysts, Final Grant Report, Contract NAG2-90, Massachusetts Institute of Technology Cambridge, MA.
- Martini, F., 1989, Fundamentals of Anatomy and Physiology, Prentice Hall, Englewood Cliffs, New Jersey, pp 748.
- Mc Cray, S.B., et al, 1990, Preliminary Evaluation of a Membrane based system for Removing CO<sub>2</sub> from air, Paper No 901295, Twentieth Intersociety Conference on Environmental Systems, Williamsburg, Virginia.
- Minemoto, M., et al, 1989, Study of Air Revitalization System for Space Station, Paper No 891576, Nineteenth Intersociety Conference on Environmental Systems, San Diego, California.
- Moran, M.J., 1982, Availability Analysis : A Guide to Efficient Energy Use, Prentice Hall, Englewood Cliffs, New Jersey.
- NASA Life Support Database, 1992, Build 2.0 Beta, Developed by Systems Evaluation and Integration Branch, Advanced Life Support Division, NASA Ames Research Center, Moffett Field, California.
- NASATM 4075, 1988, Exploration Studies Technical Report, FY 1988 Status, Volume 1, Technical Seminar.
- National Commission on Space, 1986, Pioneering the Space Frontier, Bantam Books, pp 211.
- Pass More, R., Robson, J.S., 1969, A Companion to medical studies, Volume 1, Blackwell Scientific Publications, Oxford and Edinburgh, pp 42.7.



- Perez,R., Torroglosa,V., 1991, ECOSIM - An Environmental Control Simulation Software, Paper No 911543, Twentyfirst Intersociety Conference on Environmental Systems, San Francisco, California.
- Popoma,D.,C., and Collins,V.,C., February 1965, Space Vehicle Water Reclamation Systems, AIChE Preprint Number 54A.
- Quatrone,P.,D., 1981, Extended Mission Life Support Systems, AAS 81-237.
- Ray,C.,D., et al, 1987, The Space Station Air Revitalization Subsystem Design Concept, paper No 871448, Seventeenth Intersociety Conference on Environmental Systems, Seattle, Washington.
- Reistad,G.,M., 1980, Available - Energy Utilization in the United States, Thermodynamics : Second Law Analysis, A.C.S Symposium series, 122, 93.
- Rummel,J.,D., 1990, Long Term Life Support for Space Exploration, Paper No 901277, Twentieth Intersociety Conference on Environmental Systems, Williamsburg, Virginia.
- Sacco,Jr.,A., and Reid,R.,C., July 1978, Limitations on Water Production in the Iron - Catalyzed Bosch process, ASME Paper No 78-ENAs-4, 8th International Society on Environmental Systems.
- Sadeh,W.,Z., and Condran,M.,J., 1989, A Model of Human Metabolic Mass flow rates for an engineered closed Ecosystem, Paper No 891446, Nineteenth Intersociety Conference on Environmental Systems, San Diego, California.
- Schubert,F.,H., 1983, Phase Change Recovery Techniques : Vapor Compression Distillation and Thermoelectric/Membrane Concepts, Paper No 831122, Thirteenth Intersociety Conference on Environmental Systems, San Francisco, California.

- Schubert,F.,H., June 1974, A study of the Integration of the Electrochemical Depolarized Carbondioxide Concentrator and the Bosch CO<sub>2</sub> Reduction Subsystem, Final Report, Contract NAS8-29623, ER-185-4, Life Systems Inc., Cleveland, Ohio.
- Seader,J.,D., and Nevers,N.,D., 1980, Lost Work. A mesure of Thrmodynamic Efficiency, Energy 5, pp 757-769.
- Seagrave,R.,C., 1971, Biomedical Applications of Heat and Mass Transfer, Iowa State University Press, Ames, Iowa.
- Seshan,P.,K., et al, 1991, Human Life Support During Interplanetary Travel and Domicile, Part 2 : Generic Modular Flow Schematic Modeling, Paper No 911322, Twentieth Intersociety Conference on Environmental Systems, San Francisco, California.
- Sherman,H.,C., 1952, Chemistry of Food and Nutrition, 8th ed, The Mac Million Company, New York, pp 154-176.
- Simon,R., et al, 1991, Requirements for ECLSS Simulation Software, Paper No 911542, Twentyfirst Intersociety Conference on Environmental Systems, San Francisco, California.
- Smith,J.,M., and Van Ness,H.,C., 1987, Introduction to Chemical Engineering Thermodynamics, 4th ed,McGraw-Hill Book Company, pp 548-564.
- Southgate,D.,A.,T., and Durnin,J.,V.,G.,A., 1970, Calorie Conversion factors, An experimental reassessment of the factors used in the energy value of human diets, Br.J.Nutr, pp 517-535.
- Spina,L., and Lee,M.,C., Comparison of CO<sub>2</sub> Reduction Process - Bosch and Sabatier, Paper No 851343, Fiftenth Intersociety Conference on Environmental Systems, Portalnd, Oregon.

- Stegeman,J., 1977, Exercise Physiology, 2nd ed, Georg Thieme Verlag, Stuggart, Germany, pp 192.
- Stodola,A., 1898, Zeitschrift, VDI, 32, 1086.
- Stokes,G.B., 1988, Estimating the energy content of nutrients, Trends in Biochemical Sciences, 13, pp 422 - 424.
- Takahashi,Y.,and Ohya,H., 1985, Wet - Oxidation Waste Management System for CELSS, Paper No 851398, Fifteenth Intersociety Conference on Environmental Systems, San Francisco, California.

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## APPENDIX 1

DETAILED DERIVATION OF EQUATIONS USED FOR THE COMPARTMENT  
MODEL OF THE HUMAN RESPIRATORY TRACT

Upper Respiratory Tract

Ideal gas law holds good . Therefore:

$$Q_1 / (70 + 460) = Q_2 / (98.6 + 460) \quad (A1)$$

Lower Respiratory Tract

$$\begin{aligned} \text{Volume of water entering the compartment} &= 15 / (760 - 15) \\ &= 0.021 \quad \text{lit/lit of dry gas} \end{aligned}$$

$$\begin{aligned} \text{Volume of water leaving the compartment} &= 47 / (760 - 47) \\ &= 0.066 \quad \text{lit/lit of dry gas} \end{aligned}$$

$$\begin{aligned} \text{Volume of dry gas entering} &= Q_2 - 0.021 \times Q_2 \\ &= 0.98 \times Q_2 \quad \text{lit} \end{aligned}$$

$$\begin{aligned} \text{Total volume of water present in outgoing gas} &= 0.066 \times 0.98 \times Q_2 \\ &= 0.065 \times Q_2 \quad \text{lit} \end{aligned}$$

Thereby total volume of gas leaving the compartment (Q3) is given by :

$$Q_3 = (0.065 + 0.98) \times Q_2 \quad (A2)$$

Since no exchange of N<sub>2</sub>, CO<sub>2</sub> or O<sub>2</sub> occurs in the lower respiratory tract.

Therefore the outgoing mole fractions of O<sub>2</sub>, CO<sub>2</sub> and N<sub>2</sub> will be given by

$$Y_X^i \times Q_2 = Y_X^o \times Q_3 \quad (A3)$$

where  $Y_X^i$  mole fraction of species x (may be O<sub>2</sub>, CO<sub>2</sub> or N<sub>2</sub>) in Q<sub>2</sub>  
 $Y_X^o$  mole fraction of species x in Q<sub>3</sub>

Lungs :

Solving equations (21) to (24) as given in chapter 3

$$Q_4 = (Q_3 \times (Y_{O_2^i} + Y_{CO_2^i} + Y_{N_2^i}) - VO_2 + VCO_2) / 0.938 \quad (A4)$$

The concentration of the outgoing gas from the lungs is calculated using the following equations :

$$Y_{O_2} = ((Q_3 \times Y_{O_2^i}) - VO_2) / Q_4 \quad (A5)$$

$$Y_{CO_2} = ((Q_3 \times Y_{CO_2^i}) + VCO_2) / Q_4 \quad (A6)$$

$$Y_{N_2} = (Q_3 \times Y_{N_2^i}) / Q_4 \quad (A7)$$

$Q_1, Q_2, Q_3, Q_4, VO_2, VCO_2, V_E, Y_{O_2}, Y_{N_2}$  and  $Y_{CO_2}$  are as defined in chapter 3.

$MO_2$  the volume of  $O_2$  required for metabolism is related to  $VO_2$  by,

$$MO_2 = (VO_2 / 60.0) \times (273 / 310) \quad (A8)$$

and

$$Q_3 = V_E \times 60.0 \quad (A9)$$

The total mass flow rates in lb/hr of component  $i$  (where  $i$  can be  $O_2, N_2, CO_2$  or  $H_2O$ ) in expired air ( $M_i^{exp}$ ) and in inspired air ( $M_i^{ins}$ ) is given by :

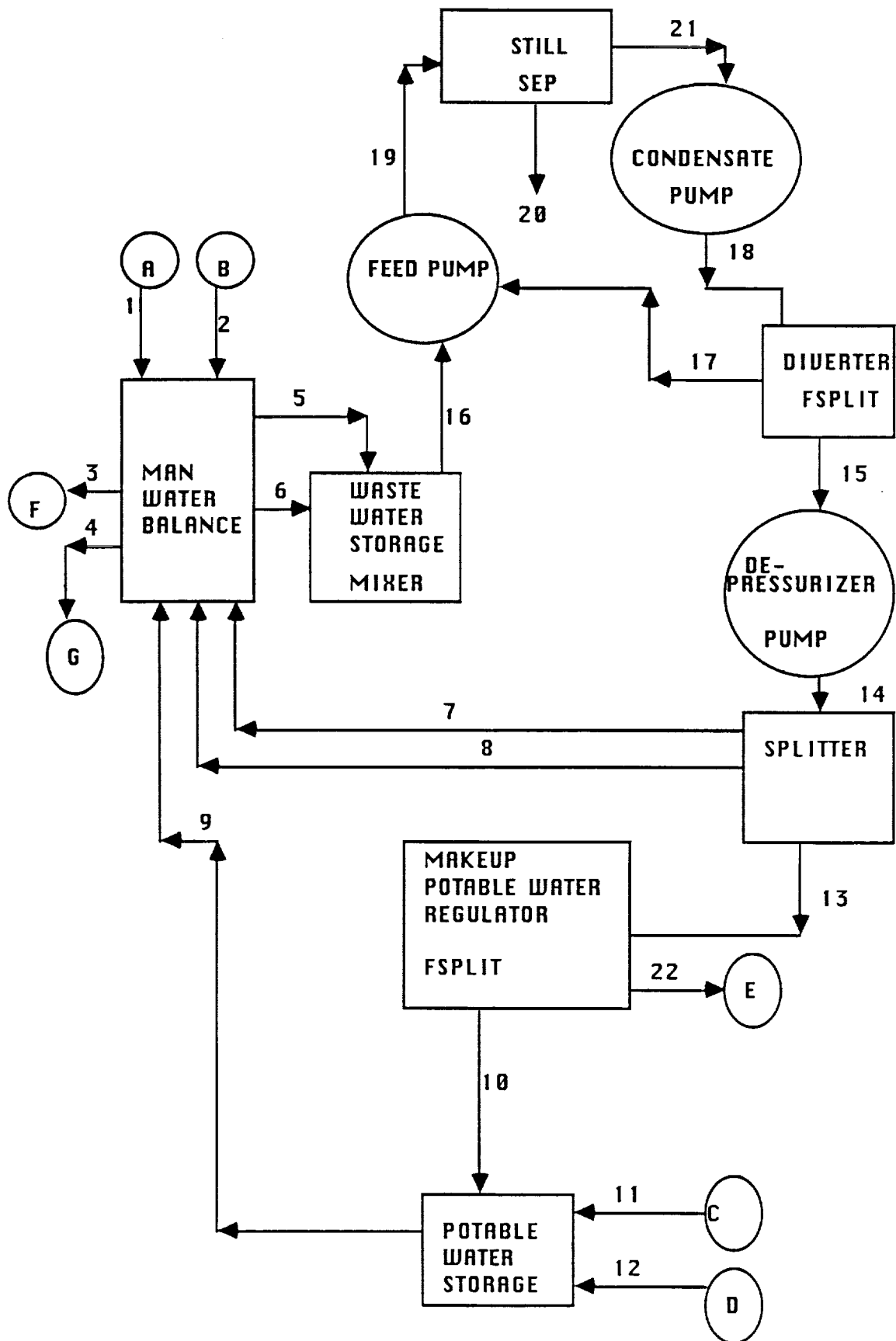
$$M_i^{exp} = (Q_4 \times Y_i \times \text{molecular weight of } i \times 0.035) / (0.7302 \times 558.6) \quad (A10)$$

$$M_i^{ins} = (Q_4 \times Y_i^i \times \text{molecular weight of } i \times 0.035) / (0.7302 \times 530.0) \quad (A11)$$

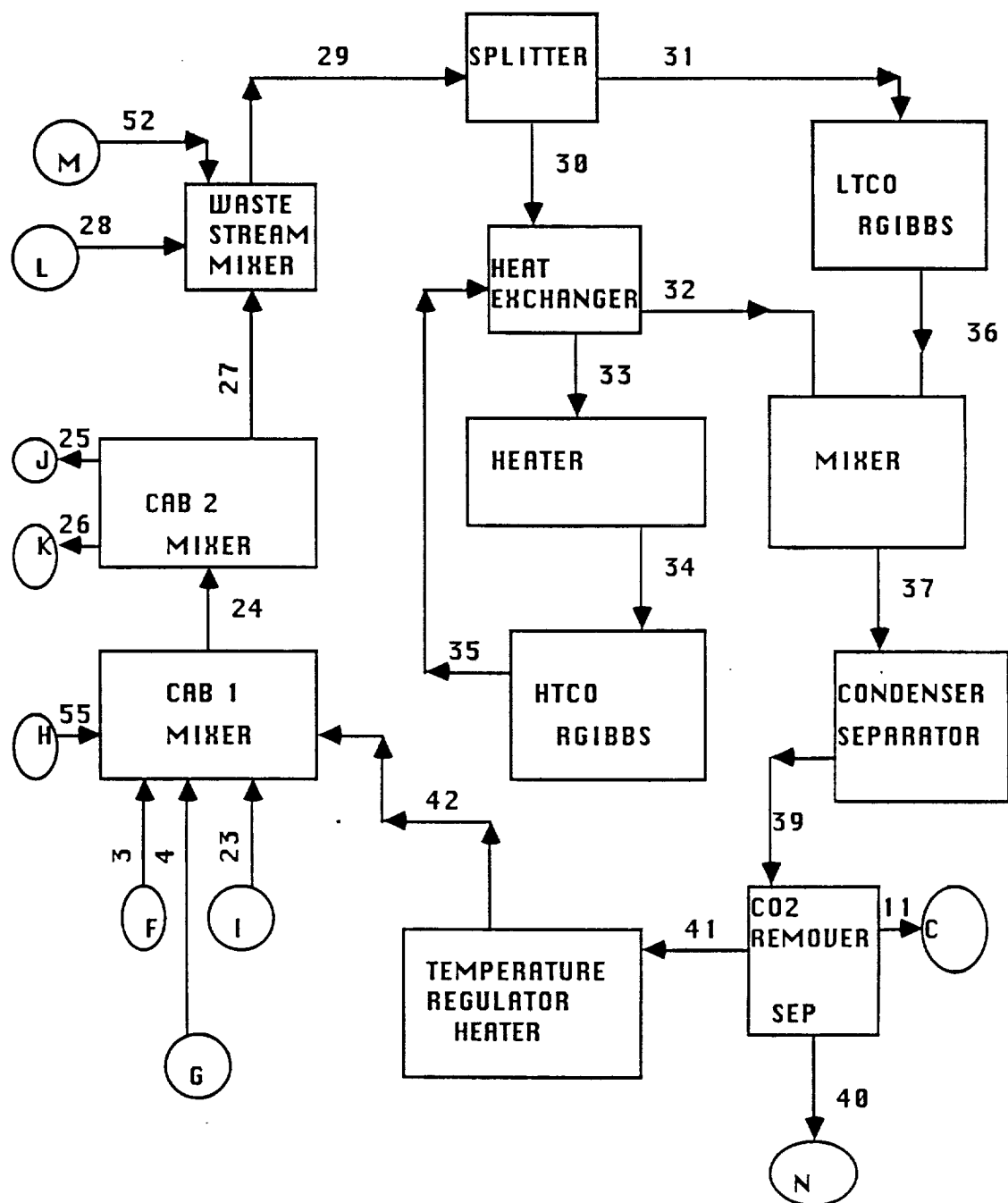
## APPENDIX 2

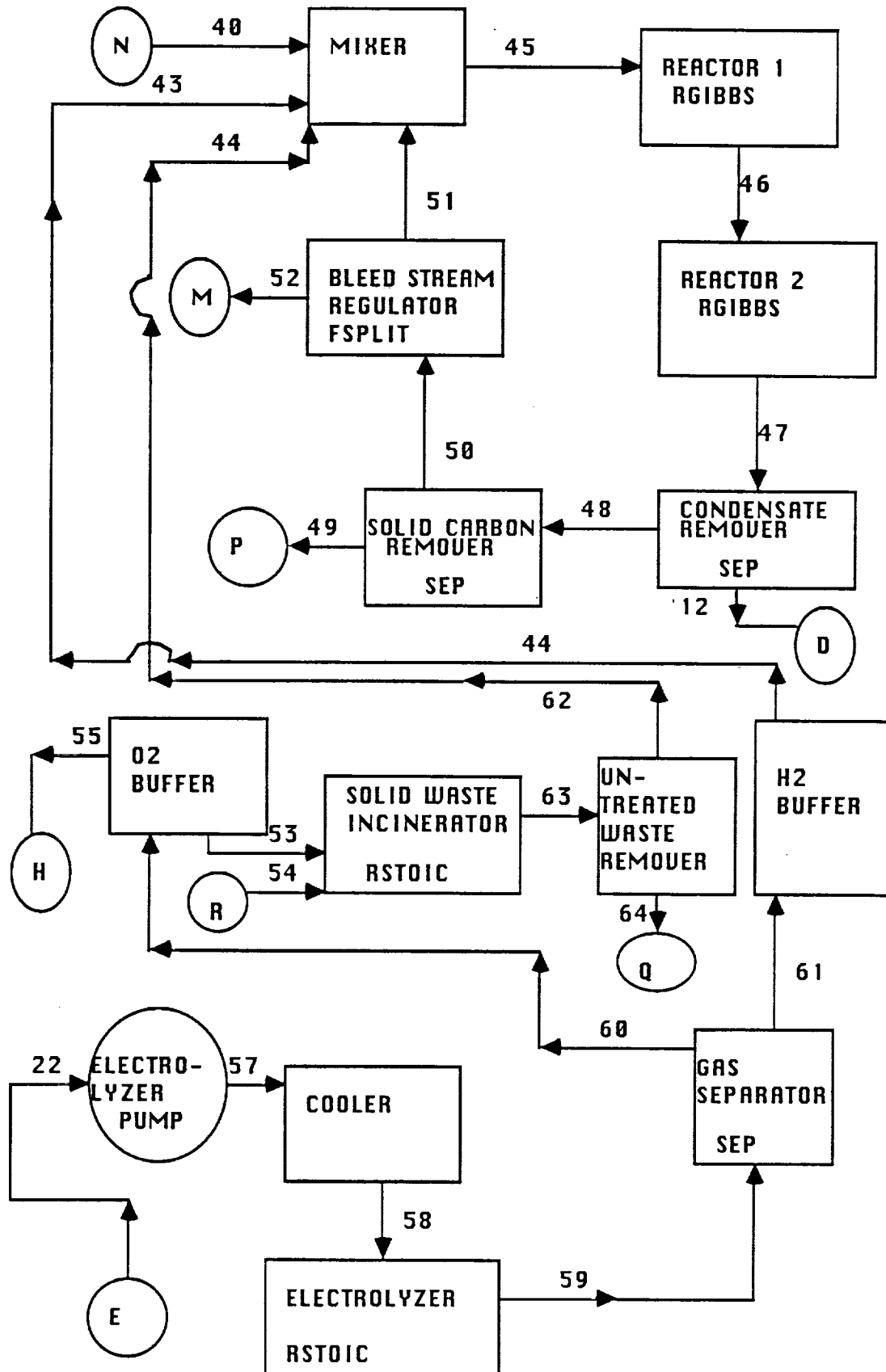
### BLOCK FLOW DIAGRAM OF THE INTEGRATED ECLSS MODEL WITH THE CREW

The integrated ASPEN model of the ECLSS is included here. Man is shown as a regular block.







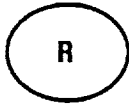


**NOMENCLATURE :**

<b>A</b>	<b>WATER PRESENT IN FOOD</b>
<b>B</b>	<b>WATER GENERATED DUE TO METABOLISM OF FOOD</b>
<b>C</b>	<b>HUMIDITY CONDENSATE</b>
<b>D</b>	<b>CONDENSATE WATER FROM CO<sub>2</sub> REDUCTION</b>
<b>E</b>	<b>WATER USED FOR OXYGEN GENERATION</b>
<b>F</b>	<b>SWEAT GENERATED BY THE CREW</b>
<b>G</b>	<b>EXCESS WATER USED FOR SATURATING THE EXPIRED AIR</b>
<b>H</b>	<b>MAKEUP OXYGEN FROM THE BUFFER TO THE CABIN</b>
<b>I</b>	<b>EXPIRED AIR FROM THE CREW</b>
<b>J</b>	<b>AIR LEAK FROM THE CABIN</b>
<b>K</b>	<b>AIR INSPIRED BY THE CREW</b>
<b>L</b>	<b>TRACE CONTAMINANT STREAM</b>
<b>M</b>	<b>BLEED STREAM FROM THE CARBON DIOXIDE REDUCTION PROCESS</b>
<b>P</b>	<b>SOLID CARBON GENERATED IN THE BOSCH REACTOR</b>

NOMENCLATURE CONTINUED :

UNTREATED SOLID WASTE



SOLID WASTE FROM CREW TO BE TREATED

## APPENDIX 3

THIS IS AN ASPEN SOLUTION CONSIDERING THE MAN IN THE CABIN  
; APPENDING EACH ECLSS MODULE TO THE CABIN BLOCK

```
; SPECIFYING THE UNIT SYSTEM FOR INPUT INFORMATIN
IN-UNITS ENG
; SPECIFYING THE UNIT SYSTEM FOR OUTPUT INFORMTION
OUT-UNITS ENG
;DEFINE COMPONENTS THAT ARE IN THE SYSTEM
COMPONENTS C1 WATER/CO2 CO2 /C3 HYDROGEN/C4 NITROGEN/C5 OXYGEN/C6 CH4
COMPONENTS C7 CARBON-MONOXIDE/C9 ACETYLENE/C12 C
COMPONENTS C13 ETHYLENE/C14 ETHANE/C2 UREA
DATABANKS SOLIDS/DIPPRPCD
; SECIFYING PHYSICAL PROPERTY OPTIONS
PROPERTIES SYSOP0
```

```
; FLOWSHEET SECTION OF ASPEN INPUT FILE
; THIS SECTION IS FOR WATER REGENERATION SUBSYSTEM
```

## FLOWSHEET WATERREGENERATION

BLOCK HEAT11	IN=METW PW01 FOODW	OUT=HE11OUT
BLOCK WASEP	IN=HE11OUT	OUT=WAEX1
BLOCK W1	IN=URINE	OUT=URINE1
BLOCK MIX12	IN=URINE1 S11 FD1U	OUT=FD1OUT
BLOCK MIX18	IN=S2 MAKEUPS2	OUT=S21
BLOCK MIX15	IN=S21 SS2	OUT=FD2OUT
BLOCK MIX13	IN=FD1OUT FD2OUT	OUT=F1
BLOCK SPTT2	IN=CON1	OUT=CON2 CONR
BLOCK STILL	IN=FOUT	OUT=CON BRINE
BLOCK P1	IN=F1 CONR	OUT=FOUT
BLOCK P4	IN=CON	OUT=CON1
BLOCK P5	IN=CON2	OUT=CON3
BLOCK SPTT3	IN=CON3	OUT=S1 S2 S3
BLOCK SPTT4	IN=S3	OUT=S3OUT MAKEUPPOT
BLOCK MIX20	IN=S1 URFLUSH	OUT=S11
BLOCK W2	IN=WA	OUT=WA1
BLOCK POTMIX	IN=MAKEUPPOT DECAN WA1	OUT=PWO
BLOCK POTSEP	IN=PWO	OUT=PWO1 PWOEX

```
; THIS SECTION IS FOR TRACE REMOVAL, DEHUMIDIFICATION, CO2
; REMOVAL, AND PART OF CO2 REDUCTION
```

## FLOWSHEET INITIAL

BLOCK CAB1	IN=N2O2 CABCO2 CABH2O EXHAIR SW	OUT=CAB1OUT
BLOCK CAB2	IN=CAB1OUT	OUT=AIRLEAK INSAIR AIROUT
BLOCK MIX2	IN=AIROUT TC BLEED1 EX	OUT=OUTM
BLOCK SPLT1	IN=OUTM	OUT=LT HT
BLOCK HEEX1	IN=HT HEIN	OUT=HEOUT2 HEATOUT
BLOCK HEA6	IN=HEATOUT	OUT=HEA6OUT
BLOCK GIBB1	IN=HEA6OUT	OUT=HEIN
BLOCK GIBB2	IN=LT	OUT=GIBBOUT
BLOCK MIXT	IN=GIBBOUT HEOUT2	OUT=HUHXOUT
BLOCK HEA2	IN=HUHXOUT	OUT=CAIR WA
BLOCK SEP3	IN=CAIR	OUT=ABAIR1 SEPC EX

```

BLOCK COOL   IN=ABAIR1           OUT=ABAIR
BLOCK MIX5   IN=SEPC SEPOUT2     HYDRO WASCO21 OUT=MIX5OUT
BLOCK REAC1   IN=MIX5OUT         OUT=REA1

```

```

; THIS SECTION IS FOR REMAINING CO2 REDUCTION SUBSYSTEM
; INVOLVING SOLID CARBON AND FOR THE SOLID WASTE INCINERATOR
; SUBSYSTEM

```

# FLWSHEET MIDDLE

```

BLOCK CHNGR1 IN=REA1           OUT=REA1OUT
BLOCK REAC2   IN=REA1OUT       OUT=REA2
BLOCK HE1     IN= REA2         OUT= HE1OUT DECAN
BLOCK SEPA    IN=HE1OUT       OUT=SEPOUT SOLIDC
BLOCK SEPA1   IN=SEPOUT       OUT=SEPOUT1 BLEED
BLOCK SOLIDINC IN=SOLIDW WASO2 OUT=WASCO2A
BLOCK SOLP    IN=WASCO2A      OUT= WASCO2 WASC

```

```

; THIS SECTION INCLUDES THE O2 GENERATION SUBSYSTEM
FLWSHEET FINAL

```

```

BLOCK CHNGR3 IN=SEPOUT1       OUT=SEPOUT2
BLOCK PSFE    IN=REMWATER S31 PWOEX1 OUT=PSFEO
BLOCK HSFE    IN=PSFEO        OUT=HSFEO
BLOCK STOIC1  IN=HSFEO        OUT=STOIC1OUT
BLOCK SEPSFE  IN=STOIC1OUT    OUT=HYD1 OXYG1 REMWATER
BLOCK CHNGR7  IN=S3OUT        OUT=S31
BLOCK CHNGR8  IN=WASCO2       OUT=WASCO21
BLOCK CHNGR9  IN=BLEED        OUT=BLEED1
BLOCK CHNGR10 IN=PWOEX        OUT=PWOEX1

```

```

; SPECIFY FEED STREAMS

```

# DEF-STREAMS MIXCISLD MIDDLE WATERREGENERATION

```

STREAM EXHAIR PRES=1[ATM] TEMP=98.6 NPHASE=1
MASS-FLOW C1 0.5/CO2 0.5/C4 3.0/C5 2.0
STREAM TC PRES=1[ATM] TEMP=70.0 MASS-FLOW=3.27D-4
MASS-FRAC C7 0.84/C6 0.084/C14 0.00056/C13 0.000014/C9 0.00014/ &
C3 0.075
STREAM HYDRO PRES=1[ATM] TEMP=70.0
MASS-FLOW C3 100.0
STREAM FD1U
SUBSTREAM CISOLID TEMP=98.6 PRES=1[ATM]
MASS-FLOW C2 0.001
STREAM SS2
SUBSTREAM CISOLID TEMP=70 PRES=1[ATM]
MASS-FLOW C2 1D-5
STREAM METW TEMP=98.6 PRES=1[ATM]
MASS-FLOW C1 0.01
STREAM MAKEUPS2 PRES=1[ATM] TEMP=70.0
MASS-FLOW C1 10.0
STREAM URFLUSH TEMP=70.0 PRES=1[ATM]
MASS-FLOW C1 100.0
STREAM CABCO2 TEMP=69.0 PRES=1[ATM] NPHASE=1 PHASE=V
MASS-FLOW CO2 100.0
STREAM CABH2O TEMP=69.0 PRES=1[ATM] NPHASE=1 PHASE=V
MASS-FLOW C1 100.0

```

```

STREAM N2O2 TEMP=69.0 PRES=1[ATM] NPHASE=1 PHASE=V
  MASS-FLOW C4 100.0/C5 100.0
STREAM SOLIDW
  SUBSTREAM CISOLID PRES=1[ATM] TEMP=98.6
  MASS-FLOW C12 100.0
STREAM WASO2 TEMP=70 PRES=1[ATM]
  MASS-FLOW C5 100.0
STREAM FOODW TEMP=70 PRES=1[ATM]
  MASS-FLOW C1 100.0
STREAM SW TEMP=98.6 PRES=1[ATM] NPHASE=1 PHASE=V
  MASS-FLOW C1 100.0

```

; DESCRIPTION OF ALL THE BLOCKS INCLUDED IN THE PROGRAM

; BLOCKS FOR VCD AND MAN WATER BALANCE

```

BLOCK HEAT11 HEATER
  PARAM TEMP=98.6 PRES=1[ATM]
BLOCK WASEP FSPLIT
  PARAM PRES=1[ATM]
  MASS-FLOW WAEXH 0.5/ SW1 0.6
BLOCK MIX12 MIXER
BLOCK MIX15 MIXER
BLOCK MIX13 MIXER
  PARAM PRES=20.0
BLOCK SPTT2 FSPLIT
  FRAC CONR 0.6
BLOCK STILL SEP
  FRAC STREAM=BRINE SUBSTREAM=MIXED COMPS=C1 FRACS=0.8
  FRAC STREAM=BRINE SUBSTREAM=CISOLID COMPS=C2 FRACS=1.0
  FLASH-SPECS CON TEMP=70 PRES=0.5 NPHASE=1 PHASE=L
  FLASH-SPECS BRINE TEMP=70 PRES=0.5 NPHASE=1 PHASE=L
BLOCK P1 PUMP
  PARAM PRES=0.5 NPHASE=2 MAXIT=60 TOL=0.01
BLOCK P4 PUMP
  PARAM PRES=20.0 NPHASE=2 MAXIT=60 TOL=0.01
BLOCK P5 PUMP
  PARAM PRES=14.7 NPHASE=2 MAXIT=60 TOL=0.01
BLOCK SPTT3 FSPLIT
  MASS-FLOW S1 0.01/S2 2.3
BLOCK SPTT4 FSPLIT
  PARAM PRES=1[ATM] NPHASE=1 PHASE=L
  FRAC MAKEUPPOT 0.5
BLOCK POTMIX MIXER
BLOCK POTSEP FSPLIT
  PARAM PRES=1[ATM]
  MASS-FLOW PW01 0.1
BLOCK MIX18 MIXER
BLOCK MIX20 MIXER
BLOCK CHNGR7 CLCHNG
BLOCK CHNGR10 CLCHNG

```

; BLOCKS FOR CABIN

```

BLOCK CAB1 MIXER
BLOCK CAB2 FSPLIT
  PARAM PRES=1[ATM] NPHASE=1

```

MASS-FLOW AIRLEAK 6.5D-3  
R-FRAC AIROUT 0.98

; BLOCKS FOR TRACE REMOVAL SUBSYSTEM

BLOCK MIX2 MIXER  
PARAM PRES=1[ATM]  
BLOCK SPLT1 FSPLIT  
PARAM PRES=1[ATM]  
FRAC LT 0.7  
BLOCK HEEX1 HEATX  
PARAM T-COLD=600  
FEEDS HOT=HEIN COLD=HT  
PRODUCTS HOT=HEOUT2 COLD=HEATOUT  
BLOCK HEA6 HEATER  
PARAM TEMP=795.0  
BLOCK GIBB1 RGIBBS  
PARAM TEMP=795 PRES=1[ATM]  
PROD C1/CO2/C4/C5/C3/C7/C6  
BLOCK GIBB2 RGIBBS  
PARAM TEMP=70 PRES=1[ATM] MAXIT=100 TOL=1D-2  
PROD CO2/C1/C4/C5/C7/C6/C3  
BLOCK MIXT MIXER  
PARAM PRES=1[ATM]

; BLOCKS FOR DEHUMIDIFICATION

BLOCK HEA2 SEP  
PARAM PRES=1[ATM]  
FRAC STREAM=CAIR COMPS=C1 CO2 C4 C5 C6 C7 C3 FRACS=0.8 1.0 1.0 &  
1.0 1.0 1.0 1.0  
FLASH-SPECS WA TEMP=40 PRES=1[ATM] NPHASE=1 PHASE=L  
FLASH-SPECS CAIR TEMP=40 PRES=1[ATM] NPHASE=1 PHASE=V  
BLOCK COOL HEATER  
PARAM TEMP=69.0 PRES=1[ATM]

; BLOCK FOR CO2 REMOVAL

BLOCK SEP3 SEP  
FRAC STREAM=ABAIR1 COMPS=CO2 C1 C4 C5 FRACS=0.5 1.0 1.0 1.0  
FRAC STREAM=EX COMPS=C6 C7 C3 CO2 FRACS=1.0 1.0 1.0 0.0  
FLASH-SPECS ABAIR1 TEMP=70.0 PRES=1[ATM]  
FLASH-SPECS SEPC TEMP=70.0 PRES=1[ATM]  
FLASH-SPECS EX TEMP=70.0 PRES=1[ATM]

; BLOCKS FOR CO2 REDUCTION USING BOSCH

BLOCK MIX5 MIXER  
PARAM PRES=1[ATM]  
BLOCK REAC1 RGIBBS  
PARAM TEMP=1300[K] PRES=1[ATM]  
PROD CO2/C3/C7/C1/C6  
BLOCK CHNGR1 CLCHNG  
BLOCK REAC2 RGIBBS  
PARAM TEMP=900[K] PRES=1[ATM]  
PROD CO2/C3/C7/C6/C1/C12 S  
BLOCK HE1 SEP  
FRAC STREAM=HE1OUT SUBSTREAM=MIXED COMPS=C1 CO2 C3 C7 C6 &  
FRACS=0.0 1.0 1.0 1.0 1.0



```

FRAC STREAM=HE1OUT SUBSTREAM=CISOLID COMPS=C12 FRACS=1.0
FLASH-SPECS DECAN TEMP=40 PRES=1[ATM] NPHASE=1 PHASE=L
FLASH-SPECS HE1OUT TEMP=40 PRES=1[ATM] NPHASE=1 PHASE=V
BLOCK SEPA SEP
FRAC STREAM=SEPOUT COMPS=CO2 C3 C7 C6 FRACS=1.0 1.0 1.0 1.0
FLASH-SPECS SOLIDC TEMP=70 PRES=1[ATM] NPHASE=1 PHASE=S
FLASH-SPECS SEPOUT TEMP=70 PRES=1[ATM] NPHASE=1 PHASE=V 1.0
BLOCK SEPA1 FSPLIT
PARAM PRES=1[ATM]
FRAC BLEED 0.0

BLOCK CHNGR3 CLCHNG

; BLOCKS FOR O2 GENERATION BY WATER ELECTROLYSIS
BLOCK PSFE PUMP
PARAM PRES=30.0
BLOCK HSFE HEATER
PARAM PRES=30.0 TEMP=70.0
BLOCK STOIC1 RSTOIC
PARAM TEMP=70.0 PRES=150.0
STOIC 1 MIXED C1 -1/C3 1/C5 0.5
CONV 1 MIXED C1 1.0
BLOCK SEPSFE SEP
PARAM PRES=14.7
FRAC STREAM=HYD1 COMPS=C3 FRACS=1.0
FRAC STREAM=OXYG1 COMPS=C5 FRACS=1.0
FLASH-SPECS HYD1 PRES=14.7 TEMP=70.0
FLASH-SPECS OXYG1 PRES=14.7 TEMP=70.0
FLASH-SPECS REMWATER PRES=14.7 TEMP=70.0

; BLOCKS FOR SOLID WASTE INCINERATOR
BLOCK SOLIDINC RSTOIC
PARAM TEMP=350 PRES=1067.0
STOIC 1 CISOLID C12 -1/MIXED C5 -1/CO2 1
CONV 1 CISOLID C12 1.0
BLOCK SOLP SEP
PARAM PRES=14.7
FRAC STREAM=WASC SUBSTREAM=CISOLID COMPS=C12 FRACS=1.0
FRAC STREAM=WASC SUBSTREAM=MIXED COMPS=CO2 C5 FRACS=0.0 0.0
FLASH-SPECS WASC PRES=14.7 TEMP=70.0 NPHASE=1 PHASE=S
FLASH-SPECS WASCO2 PRES=14.7 TEMP=70.0 NPHASE=1 PHASE=V

BLOCK W1 CLCHNG
BLOCK W2 CLCHNG
BLOCK CHNGR8 CLCHNG
BLOCK CHNGR9 CLCHNG

; DESIGN SPECS TO SET THE CABIN ENVIRONMENT BY REGULATING THE DIFFERENT
; GAS FLOW RATES INTO THE CABIN
DESIGN-SPEC NITR
F COMMON/USRINP/B33,B11,B44,B22,NM,NW,A88
DEFINE A1 MASS-FLOW STREAM=INSAIR COMPONENT=C4
SPEC A1 TO B33
TOL-SPEC 1D-3
VARY MASS-FLOW STREAM=N2O2 COMPONENT=C4

```

LIMITS 1D-1 50000.0

DESIGN-SPEC WAT

DEFINE A2 MASS-FLOW STREAM=INSAIR COMPONENT=C1  
 SPEC A2 TO B44  
 TOL-SPEC 1D-3  
 VARY MASS-FLOW STREAM=CABH2O COMPONENT=C1  
 LIMITS 0 1000.0

DESIGN-SPEC OXY

DEFINE A3 MASS-FLOW STREAM=INSAIR COMPONENT=C5  
 SPEC A3 TO B11  
 TOL-SPEC 1D-3  
 VARY MASS-FLOW STREAM=N2O2 COMPONENT=C5  
 LIMITS 1D-1 5000.0

DESIGN-SPEC CARDI

DEFINE A4 MASS-FLOW STREAM=INSAIR COMPONENT=CO2  
 SPEC A4 TO B22  
 TOL-SPEC 1D-3  
 VARY MASS-FLOW STREAM=CABCO2 COMPONENT=CO2  
 LIMITS 0 1000.0

CONVERGENCE ALSPC NEWTON

SPEC NITR / OXY / CARDI /WAT  
 PARAM MAXIT=100

; THIS IS A FORTRAN BLOCK TO SIMULATE THE BIOLOGICAL ACTIVITIES IN A MAN  
 FORTRAN MAN

```
F      COMMON/USRINP/B33,B11,B44,B22,NM,NW,A88
F      DIMENSION CA1(2),VO2(2),VCO2(2),MO2(2),VE(2),Q3(2),Q2(2)
F      DIMENSION Q1(2),YO2I3(2),YCO2I3(2),YN2I3(2),YH2OI3(2),YO2T(2)
F      DIMENSION YN2T(2),YO2M(2)
F      DIMENSION YCO2M(2),YN2M(2),YH2OM(2),YO2IM(2),YN2IM(2),YCO2T(2)
F      DIMENSION YCO2IM(2),YH2OIM(2),UR(2),H2OM(2),SWEAT(2)
F      DIMENSION TFOOD(2),TW(2),TFAT(2),TPRO(2),TCARB(2),HU(2)
F      DIMENSION CW(2),OXYG(2),HFOOD(2),DRINK(2),S(2),Q4(2)
F      REAL*8 MO2
F      DEFINE A11 MASS-FLOW STREAM=EXHAIR COMPONENT=C5
F      DEFINE A22 MASS-FLOW STREAM=EXHAIR COMPONENT=CO2
F      DEFINE A33 MASS-FLOW STREAM=EXHAIR COMPONENT=C4
F      DEFINE A44 MASS-FLOW STREAM=EXHAIR COMPONENT=C1
F      DEFINE TRACE STREAM=VAR STREAM=TC VARIABLE=MASS-FLOW
F      DEFINE WRU MASS-FLOW STREAM=FD1U SUBSTREAM=CISOLID COMPONENT=C2
F      DEFINE CAR MASS-FLOW STREAM=SOLIDW SUBSTREAM=CISOLID COMPONENT=C12
F      DEFINE OXY MASS-FLOW STREAM=WASO2 COMPONENT=C5
F      DEFINE A55 MASS-FLOW STREAM=METW COMPONENT=C1
F      DEFINE A66 MASS-FLOW STREAM=SW COMPONENT=C1
F      DEFINE A99 MASS-FLOW STREAM=FOODW COMPONENT=C1
F      DEFINE A12 BLOCK-VAR BLOCK=CAB2 SENTENCE=R-FRAC &
F          VARIABLE=FRAC ID1=AIROUT
F      OPEN(UNIT=61,FILE='INFO.DAT',STATUS='OLD')
F      OPEN(UNIT=65,FILE='SPACE.OUT',STATUS='UNKNOWN')
F      READ(61,*)NM,NW,AM,AW,WM,WW
```

```

; NM IS THE NUMBER OF MEN
; NW IS THE NUMBER OF WOMEN
; AM IS THE AVERAGE AGE OF MAN
; AW IS THE AVERAGE AGE OF WOMEN
; WM IS THE AVERAGE WT OF MAN
; WW IS THE AVERAGE WT OF WOMEN
; EEM IS THE BASAL MET ENERGY IN KCAL PER HR FOR MEN
; EEW IS THE BASAL METABOLIC ENERGY IN KCAL PER HR FOR WOMEN

F      EEM=((WM**0.5)/(0.1015*(AM**0.1333)))/24.0
F      EEW=((WW**0.5)/(0.1127*(AW**0.1333)))/24.0
F      READ(61,*)ALM,ALW
;      ALM AND ALW ARE NO OF TIMES THE BASAL ACTIVITY LEVEL IS THE ENERGY
;      EXPENDED BY THE ACTIVITY
;      LET ATM BE THE ENERGY EXPENDED BY ONE MAN IN ONE HR IN KCAL
;      LET ATW BE THE ENERGY EXPENDED BY ONE WOMAN IN ONE HR IN KCAL
F      ATM = EEM*ALM
F      ATW = EEW*ALW
;      LET RF BE THE FAT CARB RATIO
;      LET RP BE THE PROTEIN CARB RATIO
F      RF = 0.3
F      RP = 0.35
F      X = ATM
F      DO 60 I=1,2
;      CA1 IS THE AMT OF CARB REQ IN GRAMS
F      CA1(I) = X/(4.17+RF*9.3+RP*4.3)
;      VO2 IS THE AMT OF O2 REQ IN LIT
F      VO2(I) = CA1(I)*(0.85 + 0.86*RP + 2.29*RF)
;      VCO2 IS THE AMT OF CO2 REQ IN LIT
F      VCO2(I) = CA1(I)*(0.85 + 0.71*RP + 1.59*RF)
;      YO2I IS MOLE FRACTION OF O2 REQUIRED TO BE MAINTAINED IN THE CABIN
;      YN2I IS THE MOLE FRACTION OF N2 REQUIRED TO BE MAINTAINED IN THE CABIN
;      YH2OI IS THE MOLE FRACTION OF WATER VAPOR TO BE MAINTAINED IN THE
;      CABIN
;      YCO2I IS THE MOLE FRACTION OF CO2 TO BE MAINTAINED IN THE CABIN
F      YO2I = 0.208
F      YN2I = 0.769
F      YCO2I = 0.003
F      YH2OI = 0.02
;      MO2 IS THE AMT OF O2 CONSUMED IN LIT PER MIN AT STP FOR FOOD OXIDATION
F      MO2(I) = (VO2(I)/60.0)*0.88
;      WE MAKE USE OF A LINEAR RELATIONSHIP TO CALC AIR INTO THE LUNGS
;      VE IS THE VENTILLATION RATE IN LIT PER MIN AT BTP AND SATURATED
F      VE(I) = (24.55*MO2(I)) + 0.1125
;      Q3 IS THE AIR INTO THE LUNGS IN LIT PER HR
F      Q3(I) = VE(I) * 60.0
;      LET OH BE THE AMT OF WATER PRESENT IN Q1 AS ML OF WATER PER ML OF DRY
;      AIR
F      OH = (YH2OI*760.0)/(760.0 - (YH2OI*760.))
;      IN THE OUTGOING GAS AMT OF WATE PRESENT PER LIT OF DRY GAS IS
;      GIVEN BY ( 47/(760.0 -47)) = 0.066
;      LET Q2 BE THE VOL OF AIR ENTERING THE NASOPHARYNX IN LIT
F      Q2(I) = Q3(I)/((1-OH)*(1+0.066))
;      LET Q1 BE HE VOL OF AIR ENTERING THE NASAL PSG IN LIT

```

```

F      Q1(I) = Q2(I)/1.054
; NOW TO FIND OUT MOLE FRACTION OG GASES ENTERING THE LUNGS
F      YO2I3(I) = YO2I * (Q2(I)/Q3(I))
F      YCO2I3(I) = YCO2I * (Q2(I)/Q3(I))
F      YN2I3(I) = YN2I * (Q2(I)/Q3(I))
F      YH2OI3(I) = 0.062
; LET Q4 BE THE VOL OF AIR COMING OUT OF THE LUNGS IN LIT
F      S(I) = Q3(I)*(YO2I3(I)+YCO2I3(I)+YN2I3(I))
F      Q4(I) = ( S(I) - VO2(I) + VCO2(I))/0.938
; YO2T IS THE OUTPUT O2 CONC
; YCO2T IS THE OUTPUT CO2 CONC
; YN2T IS THE OUTPUT N2 CONC
F      YO2T(I) = ((Q3(I)*YO2I3(I)) - VO2(I))/Q4(I)
F      YCO2T(I) = ((Q3(I)*YCO2I3(I)) + VCO2(I))/Q4(I)
F      YN2T(I) = (Q3(I)*YN2I3(I))/Q4(I)
; TO FIND OUT AMT OF O2,N2,H2O,CO2 IN EXPIRED AIR IN LB PER HR
F      YO2M(I) = (Q4(I)*0.035*YO2T(I)*32.0)/(0.7302*558.6)
F      YCO2M(I) = (Q4(I)*0.035*YCO2T(I)*44.0)/(0.7302*558.6)
F      YN2M(I) = (Q4(I)*0.035*YN2T(I)*28.0)/(0.7302*558.6)
F      YH2OM(I) = (Q4(I)*0.035*0.062*18.0)/(0.7302*558.6)

;TO FIND OUT AMT OF GAS IN INSPIRED AIR IN LB PER HR
F      YO2IM(I) = (Q1(I)*0.035*YO2I*32.0)/(0.7302*530.0)
F      YN2IM(I) = (Q1(I)*0.035*YN2I*28.0)/(0.7302*530.0)
F      YCO2IM(I) = (Q1(I)*0.035*YCO2I*44.0)/(0.7302*530.0)
F      YH2OIM(I) = (Q1(I)*0.035*YH2OI*18.0)/(0.7302*530.0)

; LET UR BE THE AMT OF UREA IN URINE IN LB PER HR
F      UR(I) = CA1(I)*RP*0.337*0.0022
; LET H2OM BE AMT OF METABOLIC WATER PRODUCED IN LB PER HR
F      H2OM(I) = CA1(I)*(0.6 + (1.125*RF)+(0.51*RP))*0.0022
; LET SWEAT BE THE AMT OF WATER LOST AS SWEAT IN LB PER HR
F      IF(X.LE.250.0) GO TO 41
F      SWEAT(I) = ((2.5*X) - 325.0)*0.0022
F      GO TO 42
F 41      SWEAT(I) = ((1.50*X) - 75)*0.0022

; HU IS THE AMT OF WATER IN URINE IN LB PER HR
F 42      HU(I) = UR(I)*69.22
; LET TFAT BE HE TOTAL FAT IN DIET IN GM
; LET TPRO BE THE TOTAL PROTEIN IN DIET IN GM
; LET TCARB BE THE TOTAL CARB IN DIET IN GMS
F      TFAT(I) = CA1(I)*1.02*RF
F      TPRO(I) = CA1(I)*1.07*RP
F      TCARB(I) = CA1(I)*1.02
; LET TFOOD BE THE TOTAL FOOD IN DIET IN GM PER HR
F      TFOOD(I) = TFAT(I) + TPRO(I) + TCARB(I)
; LET TW BE THE TOTAL WASTE IN GM PE HR
F      TW(I) = CA1(I)*(0.02 + (0.02*RF)+(0.07*RP))
; LET CW BE THE TOTAL CARBON CONTENT OF WASTE IN GM PER HR
F      CW(I) = CA1(I)*((0.4*0.02)+(0.758*0.02*RF)+(0.312*0.07*RP))
;LET OXYG BE THE TOTAL O2 REQ TO BURN THE FECES IN LB PER HR
F      OXYG(I) = CW(I)*0.0022*(32.0/12.0)
; LET HFOOD BE AMT OF WATER IN FOOD IN LB PER HR
F      HFOOD(I) = 1.32*TFOOD(I)*0.0022

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; LET DRINK BE TOTAL AMT OF POTABLE WATER REQ IN LB PER HR
F      DRINK(I)=SWEAT(I)+HU(I)+YH2OM(I)-YH2OIM(I)-HFOOD(I)-H2OM(I)
F      X=ATW
F 60    CONTINUE

; CA, P, FA ARE THE TOTAL CARBOHYDRATE, PROTEIN, FAT REQUIRED BY THE
; CREW RESPECTIVELY (GM/HR)
F      CA = TCARB(1)*NM + TCARB(2)*NW
F      FA = TFAT(1)*NM + TFAT(2)*NW
F      P  = TPRO(1)*NM + TPRO(2)*NW
F      WRITE(65,*) 'CA',CA, 'FA',FA, 'P',P

; A11,A22,A33,A44 ARE THE TOTAL AMOUNT OF O2,CO2,N2 AND WATER
; RESPECTIVELY WHICH ARE PRESENT IN THE TOTAL MASS OF EXPIRED AIR INTO ;THE
; CABIN BY ALL THE CREW MEMBERS
F      A11 = YO2M(1)*NM + YO2M(2)*NW
F      A22 = YCO2M(1)*NM + YCO2M(2)*NW
F      A33 = YN2M(1)*NM + YN2M(2)*NW
F      A44 = YH2OM(1)*NM + YH2OM(2)*NW

; B11,B22,B33,B44 ARE THE TOTAL AMOUNT OF O2,CO2,N2 AND WATER
; RESPECTIVELY WHICH ARE PRESENT IN THE TOTAL MASS OF INSPIRED AIR BY
; ALL THE CREW MEMBERS.
F      B11 = YO2IM(1)*NM + YO2IM(2)*NW
F      B22 = YCO2IM(1)*NM + YCO2IM(2)*NW
F      B33 = YN2IM(1)*NM + YN2IM(2)*NW
F      B44 = YH2OIM(1)*NM + YH2OIM(2)*NW
; LET Q6 BE THE TOTAL VOL OF INSPIRED AIR
F      Q6 = Q1(1)*NM + Q1(2)*NW
; TRACE IS THE TOTAL MASS OF TRACE CONTAMINANT STREAM WHICH IS RELATED
; TO CREW SIZE.
F      TRACE= (NM+NW)*3.27D-4
; WRU IS THE TOTAL UREA PRODUCED BY THE CREW
F      WRU = UR(1)*NM + UR(2)*NW
; LE TOTW BE THE TOTAL AMOUNT OF SOLID WASTE GENERATED BY THE CREW
F      TOTW = TW(1)*NM + TW(2)*NW
; CAR IS THE CARBON PRESENT IN THE TOTAL SOLID WASTE FROM THE CREW
F      CAR = (CW(1)*NM + CW(2)*NW)*0.0022
F      WRITE(65,*) 'TOTW',TOTW, 'CAR',CAR
; LEP PER BE TOTAL % OF CARBON IN WASTE
F      PER = CAR/(TOTW)*0.0022
F      WRITE (65,*) 'PER',PER
; OXY IS THE TOTAL O2 REQUIRED FOR SOLID WASTE INCINERATOR
F      OXY = OXYG(1)*NM + OXYG(2)*NW
; A55 IS TOTAL METABOLIC WATER PRODUCED BY ALL THE CREW MEMBERS
F      A55 = H2OM(1)*NM + H2OM(2)*NW
; A66 IS THE TOTAL SWEAT GENERATED BY ALL THE CREW MEMBERS
F      A66 = SWEAT(1)*NM + SWEAT(2)*NW
; A77 IS THE TOTAL AMOUNT OF WATER ASSOCIATED WITH THE UREA AS URINE
F      A77 = HU(1)*NM + HU(2)*NW
; A88 IS THE TOTAL POTABLE WATER TO BE SUPPLIED AS DRINKING WATER
F      A88 = DRINK(1)*NM + DRINK(2)*NW
; A99 IS THE TOTAL WATER ASSOCIATED IN THE FOOD REQUIRED BY THE ENTIRE
; CREW
F      A99 = HFOOD(1)*NM + HFOOD(2)*NW

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; LET THEAT BE THE TOTAL HEAT LIBERATED BY THE CREW IN BTU
F      THEAT = (NM*ATM + NW*ATW)*(4187.0/1055.0)
; LET THE BUFFER TEMP OF THE GASES SUPPLIED TO THE CABIN BE 69 F
; LET Q5 BE THE VOL OF AIR TO BE SUPPLIED
F      Q5 = THEAT/(1.08*1.0)
F      A10 = (Q5*60.0)/(Q6*0.035)
F      A12 = A10 / (1+A10)
F      WRITE(65,*) 'A99',A99,'A88',A88,'A12',A12

WRITE-VARS A11 A22 A44 A33 TRACE WRU CAR OXY A55 A99 A66 &
      A12
FLASH-SPECS EXHAIR TP NPHASE=1
FLASH-SPECS METW NOFLASH
FLASH-SPECS FOODW NOFLASH

; THIS IS A FORTRAN BLOCK TO REGULATE THE WATER REQUIRED FOR SATURATING
; THE EXPIRED AIR
FORTRAN WSEPMAN
  DEFINE WSEP1 MASS-FLOW STREAM=INSAIR COMPONENT=C1
  DEFINE WSEP2 MASS-FLOW STREAM=EXHAIR COMPONENT=C1
  DEFINE WSEP3 BLOCK-VAR BLOCK=WASEP SENTENCE=MASS-FLOW &
    VARIABLE=FLOW ID1=WAEXH
  DEFINE WSEP4 MASS-FLOW STREAM=SW COMPONENT=C1
  DEFINE WSEP5 BLOCK-VAR BLOCK=WASEP SENTENCE=MASS-FLOW &
    VARIABLE=FLOW ID1=SW1
F      WSEP3 = WSEP2 - WSEP1
F      WSEP5 = WSEP4
      EXECUTE BEFORE WASEP

; THIS DESIGN SPEC IS USED TO REGULATE THE AMOUNT OF CO2 REMOVED BY
; ENSURING THAT AMOUNT OF CO2 IN THE AIR STREAM IS WHAT IS DESIRED TO BE
; SUPPLIED TO THE CABIN. HERE WE MAKE AN ASSUMPTION THAT THE EQUIPMENT
; IS AVAILABLE TO ACHIEVE THE DESIRED SEPARATION.
DESIGN-SPEC SEPAR
  DEFINE SEP1 MASS-FLOW STREAM=ABAIR1 COMPONENT=CO2
  DEFINE SEP2 MASS-FLOW STREAM=CABCO2 COMPONENT=CO2
  SPEC SEP1 TO SEP2
  TOL-SPEC 1D-3
  VARY BLOCK-VAR BLOCK=SEP3 SENTENCE=FRAC &
    VARIABLE=FRACS ID1=MIXED ID2=ABAIR1 ELEMENT=1
    LIMITS 0 1.0

; THIS FORTRAN BLOCK IS USED TO ADJUST THE AMOUNT OF H2 TO BE SUPPLIED
; TO THE BOSCH PROCESS.
FORTRAN H2ADJUST
  DEFINE HY1 MASS-FLOW STREAM=HYDRO COMPONENT=C3
  DEFINE HY2 MASS-FLOW STREAM=SEPOUT2 COMPONENT=C3
  DEFINE HY3 STREAM-VAR STREAM=HYDRO VARIABLE=VFRAC
  DEFINE CO1 STREAM-VAR STREAM=SEPC VARIABLE=MASS-FLOW
  DEFINE CO4 STREAM-VAR STREAM=WASCO21 VARIABLE=MASS-FLOW
  DEFINE CO5 MASS-FLOW STREAM=SEPOUT2 COMPONENT=CO2
F      HY1 = 2*(CO1+CO5+CO4) - HY2
F      HY3 = 1.0
F      WRITE(65,*) 'HY1',HY1,'HY3',HY3
      READ-VARS HY2 CO1 CO5 CO4

```

WRITE-VARS HY1 HY3

; THIS FORTRAN BLOCK IS USED TO CONTROL THE TEMPERATURE OF THE  
; DEHUMIDIFIER FOR THE EXIT AIR FROM THE CABIN.

FORTTRAN HUMIDIFICATION

```

DEFINE HU1 MASS-FLOW STREAM=HUHXOUT COMPONENT=C1
DEFINE HU2 MASS-FLOW STREAM=CABH2O COMPONENT=C1
DEFINE HU2A BLOCK-VAR BLOCK=HEA2 SENTENCE=FRAC &
    VARIABLE=FRACS ID1=MIXED ID2=CAIR ELEMENT=1
DEFINE HU3 STREAM-VAR STREAM=HUHXOUT VARIABLE=MASS-FLOW
DEFINE HTEMP STREAM-VAR STREAM=HUHXOUT VARIABLE=TEMP
DEFINE HTSEP1 BLOCK-VAR BLOCK=HEA2 SENTENCE=FLASH-SPECS &
    VARIABLE=TEMP ID1=WA
DEFINE HTSEP2 BLOCK-VAR BLOCK=HEA2 SENTENCE=FLASH-SPECS &
    VARIABLE=TEMP ID1=CAIR

```

```

F      HU4 = HU3 - HU1
F      HU2A = HU2/HU1
F      HYIN = HU1/HU4
F      HYOUT = HU2/HU4
F      LABAS = 1075.8
F      CS = 0.24 + 0.45*HYIN
F      HU5 = ((HYIN - HYOUT)*LABAS)/CS
F      HTSEP1 = HTEMP - HU5
F      HTSEP2 = HTEMP - HU5
F      WRITE(65,*) 'HTSEP2', HTSEP2, 'HU5', HU5
      READ-VARS HU1 HU2 HU3 HTEMP
      WRITE-VARS HTSEP1 HTSEP2 HU2A

```

; THIS DESIGN SPEC IS USED TO REGULATE THE AMOUNT OF WATER TO BE  
; SUPPLIED FOR DRINKING. THIS ENABLES TO COMPLETELY CLOSE THE WATER  
; LOOP. THE REMAINING WATER IS SENT TO THE WATER ELECTROLYSIS UNIT.

DESIGN-SPEC MAKEUPPOT

```

      DEFINE AK1 MASS-FLOW STREAM=MAKEUPPOT COMPONENT=C1
      DEFINE AK2 MASS-FLOW STREAM=DECAN COMPONENT=C1
      DEFINE AK3 MASS-FLOW STREAM=WA1 COMPONENT=C1
F      AK5 = A88 - (AK2+AK3)
F      IF (AK5.LE.0.0) GO TO 71
F      AK6 = AK5
F      GO TO 72
F 71    AK6 = 0.0
F 72    WRITE(65,*) 'AK6', AK6
      SPEC AK1 TO AK6
      TOL-SPEC 1D-3
      VARY BLOCK-VAR BLOCK=SPTT4 SENTENCE=FRAC &
          VARIABLE=FRAC ID1=MAKEUPPOT
      LIMITS 0 1.0

```

; THIS FORTRAN BLOCK IS USED TO COMPUTE THE AMOUNT OF MAKEUP HYGIENE  
; WATER REQUIRED

FORTTRAN HYGIENEMAKUP

```

      DEFINE U11 MASS-FLOW STREAM=S2 COMPONENT=C1
      DEFINE U12 MASS-FLOW STREAM=MAKEUPS2 COMPONENT=C1
F      OPEN(UNIT=90, FILE='WA.OUT', STATUS='UNKNOWN')
;      LET U13 BE THE FLOW RATE OF MAKE UP HYGIENE WATER

```

```

F      U13=2.29*(NM+NW)-U11
F      IF(U13.LT.0.0) GO TO 311
F      U12=U13
F      GO TO 312
F 311   U12=0.0
F 312   WRITE(65,*) U12,'AMT OF MAKUP HYGIENE WATER'
        EXECUTE BEFORE MIX18
        FLASH-SPECS S2 NOFLASH
        FLASH-SPECS MAKEUPS2 NOFLASH

; THIS IS A FORTRAN BLOCK TO MAINTAIN THE UREA CONC AS DESIRED IN THE
; THE HYGIENE WATER
FORTRAN URMANT
  DEFINE R1 MASS-FLOW STREAM=S21 SUBSTREAM=CISOLID COMPONENT=C2
  DEFINE R2 STREAM-VAR STREAM=SS2 SUBSTREAM=CISOLID VARIABLE=MASS-FLOW
F      OPEN(UNIT=90,FILE='WA.OUT',STATUS='UNKNOWN')
F      R22 = 5.5D-5*(NM+NW) - R1
F      IF(R22.LT.0.0) GO TO 410
F      R2=R22
F      GO TO 411
F 410   R2=0.0
F 411   WRITE(65,*)R2,'MASS FLOW OF SS2'
        EXECUTE BEFORE MIX15
        FLASH-SPECS S21 NOFLASH
        FLASH-SPECS SS2 NOFLASH

; THIS IS A FORTRAN BLOCK TO COMPUTE THE MAKEUP URINAL FLUSH WATER
; REQUIRED
FORTRAN FLUSHMAK
  DEFINE FL1 MASS-FLOW STREAM=S1 COMPONENT=C1
  DEFINE FL2 MASS-FLOW STREAM=URFLUSH COMPONENT=C1
F      FL3=(0.0454*(NM+NW)) - FL1
F      IF(FL3.LT.0.0)GO TO 99
F      FL2=FL3
F      GO TO 97
F 99    FL2=0.0
F 97    WRITE(65,*) 'URFUSH REQ',FL2
        EXECUTE BEFORE MIX20
        FLASH-SPECS S1 NOFLASH

; THIS FORTRAN BLOCK IS USED TO DETERMINE THE SPLIT FRACTION FOR THE
;PURE OBTAINED FROM THE WATER REGENERATION UNIT AS IN SPTT3
FORTRAN WATERSPLIT
  DEFINE WA1 STREAM-VAR STREAM=CON3 VARIABLE=MASS-FLOW
  DEFINE WA2 BLOCK-VAR BLOCK=SPTT3 SENTENCE=MASS-FLOW &
        VARIABLE=FLOW ID1=S1
  DEFINE WA3 BLOCK-VAR BLOCK=SPTT3 SENTENCE=MASS-FLOW &
        VARIABLE=FLOW ID1=S2
; LET HY BE THE AMOUNT OF WATER REQ FOR HYGIENE PURPOSE
; LET FLU BE THE AMOUNT OF WATER REQ FOR FLUSH PURPOSE
; THESE ABOVE VALUES ARE OBTAINED FROM NASA DATA BASE FOR A CREW OF ONE
; MEMBER
F      HY=2.29 * (NM+NW)
F      FLU=0.0454*(NM+NW)
;LET WA5 BE THE DIFF BETWEEN CON3 AND FLU AND HY

```



```

F      WA5=WA1 - (HY + FLU)
F      IF(WA5.LT.0.0)GO TO 13
F      WA2 = FLU
F      WA3 = HY
F      GO TO 133
F 13   WA2=0.02*WA1
F      WA3=0.98*WA1
F 133  WRITE(65,*) 'WA2',WA2,'WA3',WA3
      EXECUTE BEFORE SPTT3
      FLASH-SPECS CON3 NOFLASH

```

; THIS FORTRAN BLOCK IS USED TO COMPUTE THE SPLIT FRACTION FOR THE  
; CATALYTIC OXIDATION IN THE TRACE GAS TREATMENT SUBSYSTEM

FORTRAN TRACRAT

```

      DEFINE TR1 MASS-FLOW STREAM=OUTM COMPONENT=C6
      DEFINE TR2 STREAM-VAR STREAM=OUTM VARIABLE=MASS-FLOW
      DEFINE TR3 BLOCK-VAR BLOCK=SPLT1 SENTENCE=FRAC &
          VARIABLE=FRAC ID1=HT
F      TR4 = TR1/TR2
F      TR5 = (0.075/0.08)*TR4
F      IF (TR5.LE.0.075)GO TO 92
F      TR7 = TR5
F      GO TO 93
F 92   TR7 = 0.075
F 93   IF (TR7.GT.0.3)GO TO 95
F      TR3=TR7
F      GO TO 96
F 95   TR3 = 0.3
F 96   WRITE(65,*) 'TR3',TR3
      EXECUTE BEFORE SPLT1

```

; THIS FORTRAN BLOCK IS USED TO COMPUTE THE AMOUNT OF EXPENDABLES  
; STORED/CONSUMED FOR THE ENTIRE LSS

FORTRAN REQUIREMENTS

```

      DEFINE RHQ2 MASS-FLOW STREAM=HYD1 COMPONENT=C3
      DEFINE RHQ3 MASS-FLOW STREAM=HYDRO COMPONENT=C3
      DEFINE RCQ4 MASS-FLOW STREAM=ABAIR COMPONENT=CO2
      DEFINE RCQ5 MASS-FLOW STREAM=CABCO2 COMPONENT=CO2
      DEFINE RNQ6 MASS-FLOW STREAM=ABAIR COMPONENT=C4
      DEFINE RNQ7 MASS-FLOW STREAM=N2O2 COMPONENT=C4
      DEFINE ROQ8 MASS-FLOW STREAM=N2O2 COMPONENT=C5
      DEFINE ROQ9 MASS-FLOW STREAM=ABAIR COMPONENT=C5
      DEFINE ROQ10 MASS-FLOW STREAM=OXYG1 COMPONENT=C5
      DEFINE RWQ12 MASS-FLOW STREAM=CABH2O COMPONENT=C1
      DEFINE ROQ13 MASS-FLOW STREAM=WASO2 COMPONENT=C5
      DEFINE RWQ14 MASS-FLOW STREAM=MAKEUPS2 COMPONENT=C1
      DEFINE RWQ15 MASS-FLOW STREAM=URFLUSH COMPONENT=C1
      DEFINE RWQ16 MASS-FLOW STREAM=ABAIR COMPONENT=C1
      DEFINE RWQ17 STREAM-VAR STREAM=SOLIDC SUBSTREAM=MIXED &
          VARIABLE=MASS-FLOW
F      OPEN(UNIT=66,FILE='REPORT.OUT',STATUS='UNKNOWN')
; H2REQ IS AMT OF H2 IN BUFFER
F      H2REQ = RHQ2 - RHQ3
F      CO2REQ = RCQ5 - RCQ4
F      N2REQ = RNQ7 - RNQ6

```

```

; O2REQ IS AMT OF O2 STORED IN BUFFER
F      O2TCAB = ROQ8 - ROQ9
F      O2REQ =ROQ10 + ROQ9 -ROQ13 - ROQ8
F      WATREQ = RWQ12+RWQ14+RWQ15-RWQ16
F      WRITE(66,*) 'NM:',NM,'NW:',NW
F      WRITE(66,*) 'AMOUNT OF WATER REQ:',WATREQ
F      WRITE(66,*) 'AMOUNT OF OXY REQ:',O2REQ
F      WRITE(66,*) 'AMOUNT OF CO2 REQ:',CO2REQ,'AMT OF N2 REQ:',N2REQ
F      WRITE(66,*) 'AMOUNT OF H2 REQ:',H2REQ
F      WRITE(66,*) 'CARBO:',CA,'FAT:',FA,'PROTEIN:',P
F      WRITE(65,*) 'AMOUNT OF SOLIDC',RWQ17
      READ-VARS RHQ2 RHQ3 RCQ4 RCQ5 RNQ6 RNQ7 ROQ8 ROQ9 ROQ10 &
              RWQ12 ROQ13 RWQ14 RWQ15 RWQ17

; THIS IS A FORTRAN BLOCK TO DETERMINE THE WASTE OXIDIZER TEMP( A LINEAR
; RELATIONSHIP IS USED)
FORTRAN WASOTEMP
      DEFINE CTEMP BLOCK-VAR BLOCK=SOLIDINC SENTENCE=PARAM &
      VARIABLE=TEMP
F      CTEMP = ((194 - PER)/0.65)*(9/5)) + 32
F      WRITE(65,*) 'CTEMP',CTEMP,'PER',PER
      WRITE-VARS CTEMP

; THIS IS A FORTRAN BLOCK TO DETERMINE THE AMOUNT OF WATER IN BRINE.
; THIS IS TO ENSURE THAT THE OUTPUT FROM THE VCD IS A 45% CONCENTRATED
; SOLUTION
FORTRAN VCD
      DEFINE VCD1 MASS-FLOW STREAM=FOUT SUBSTREAM=CISOLID COMPONENT=C2
      DEFINE VCD2 MASS-FLOW STREAM=FOUT COMPONENT=C1
      DEFINE VCD3 BLOCK-VAR BLOCK=STILL SENTENCE=FRAC &
      VARIABLE=FRACS ID1=MIXED ID2=BRINE ELEMENT=1
F      VCD4 = 0.45*VCD1
F      VCD3 = VCD4/VCD2
F      WRITE(65,*) 'VCD3',VCD3
      READ-VARS VCD1 VCD2
      WRITE-VARS VCD3

; THIS IS A FORTRAN BLOCK TO DOUBLY ENSURE THAT THE RIGHT AMOUNT OF
; POTABLE WATER IS SUPPLIED TO THE CABIN. THE EXCESS IS SENT FOR O2
; GENERATION
FORTRAN POTAD
      DEFINE POT1 BLOCK-VAR BLOCK=POTSEP SENTENCE=MASS-FLOW &
      VARIABLE=FLOW ID1=PW01
F      POT1 = A88
F      WRITE(65,*) 'POT1',POT1
      EXECUTE AFTER POTMIX

CONV-OPTIONS
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RUN-CONTROL MAX-TIME=4000

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52-54

177402

p-29

N94-12367

# APPENDIX 2



## Body Water Compartments

The most abundant compound in the human body is water, accounting for 40% to 80% of the body weight depending upon the amount of adipose tissue present. The body contains the highest proportion of water at infancy, up to 80%, and then the water content decreases as old age is approached. The average water content of an adult male is 60% of the body weight whereas the average water content of an adult female is 50% of the body weight. This difference is due to the content of subcutaneous fat.

The total body water can be categorized as existing in two main compartments: intracellular water and extracellular water. The intracellular water consists of all the water within the cells and constitutes over half of the total body water. Since red blood cells are surrounded by plasma, and all other cells are surrounded by interstitial fluid, the intracellular compartment has been sub-divided to represent these two cell types in figure 1. The extracellular water, which includes all of the fluid outside of the cells, can be further sub-divided into compartments which represent interstitial fluid, circulating blood plasma, lymph, and transcellular water. The interstitial fluid surrounds cells outside of the vascular system whereas plasma is contained within the blood vessels. Avascular tissues such as dense connective tissue and cartilage contain interstitial water which slowly equilibrates with tracers used to determine extracellular fluid volume. For this reason, additional compartments are sometimes used to represent these avascular tissues. Lymph is interstitial fluid which has flowed into the lymphatic vessels and is eventually returned to the vascular system. A small fraction of the extracellular fluid is separated from other extracellular compartments by a layer of epithelium. This compartment, which includes cerebrospinal fluid, aqueous and vitreous humor, synovial fluid, and fluid secretions of glands, makes up the transcellular compartment. These body water compartments, and the interactions between them, are shown in figure 1. The average size of each compartment, in terms of percent body weight, has been determined for adult males and females (West, 1985) and is included in this figure. The lymph compartment, which is often included in the interstitial compartment, has been determined to be approximately 2.0% of the body weight (Pitts, 1974). The size of the lymph compartment for females was determined by multiplying 2.0% by 5/6 (recall that the average female body is 50% water and the average male body is 60% water).

Cerebrospinal fluid and aqueous humor, which make up a part of the transcellular compartment, are formed by epithelial cells secreting sodium ions into the associated chamber (Guyton, Taylor, & Granger, 1975). The secretion of positively charged sodium ions creates a potential difference, with respect to the blood, thereby causing negatively charged ions to flow from the plasma, into the epithelial cells, and eventually into the chambers. The excess ions then cause water to flow across the epithelial membranes by osmosis. Therefore, water flows from the intracellular fluid of the epithelial cells into the chambers by osmosis. Since osmosis is also the primary force for the flow of water between the cellular compartment and the interstitial compartment, and since

the transcellular compartment accounts for less than 2% of the body weight, this compartment has been lumped together with the interstitial compartment in figure 1.

## Osmosis

Osmosis refers to the movement of solvent across a semipermeable membrane which is permeable to solvent but not to solutes. A cell membrane, which is freely permeable to water but not to most solutes, is an example of such a semipermeable membrane. Osmosis is similar to diffusion in that a concentration gradient is the driving force behind the movement of molecules, however, diffusion refers to the movement of solute molecules whereas osmosis refers to the movement of solvent molecules. Additionally, osmosis and diffusion occur in opposite directions since when the concentration of solute molecules is high, the concentration of water must be low. The process of osmosis is illustrated in figure 2, where the small spheres represent water molecules and the large spheres represent solute molecules. The two solutions on each side of the semipermeable membrane initially have different solute concentrations (step 1). The solvent molecules, in this case water, begin crossing the membrane from the side with the lower solute concentration to the side with the higher solute concentration. This process continues until the concentration solute is the same on both sides (step 2a). The larger the solute concentration difference on each side, the stronger the driving force, or osmotic force, for water movement. This osmotic force is sometimes called the osmotic pressure. If a downward pressure is applied to side b (step 2b), the movement of water across the membrane can be eliminated and this downward pressure is equal to the osmotic pressure.

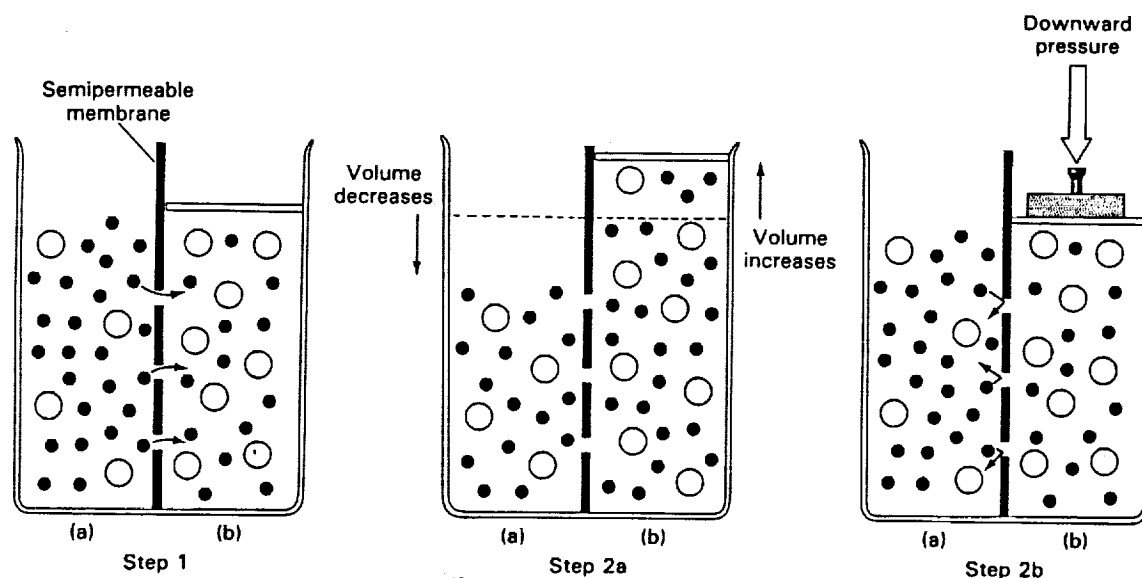


Figure 2: An example of osmosis where the small spheres represent water molecules and the large spheres represent solute molecules. (taken from Martini, 1989)

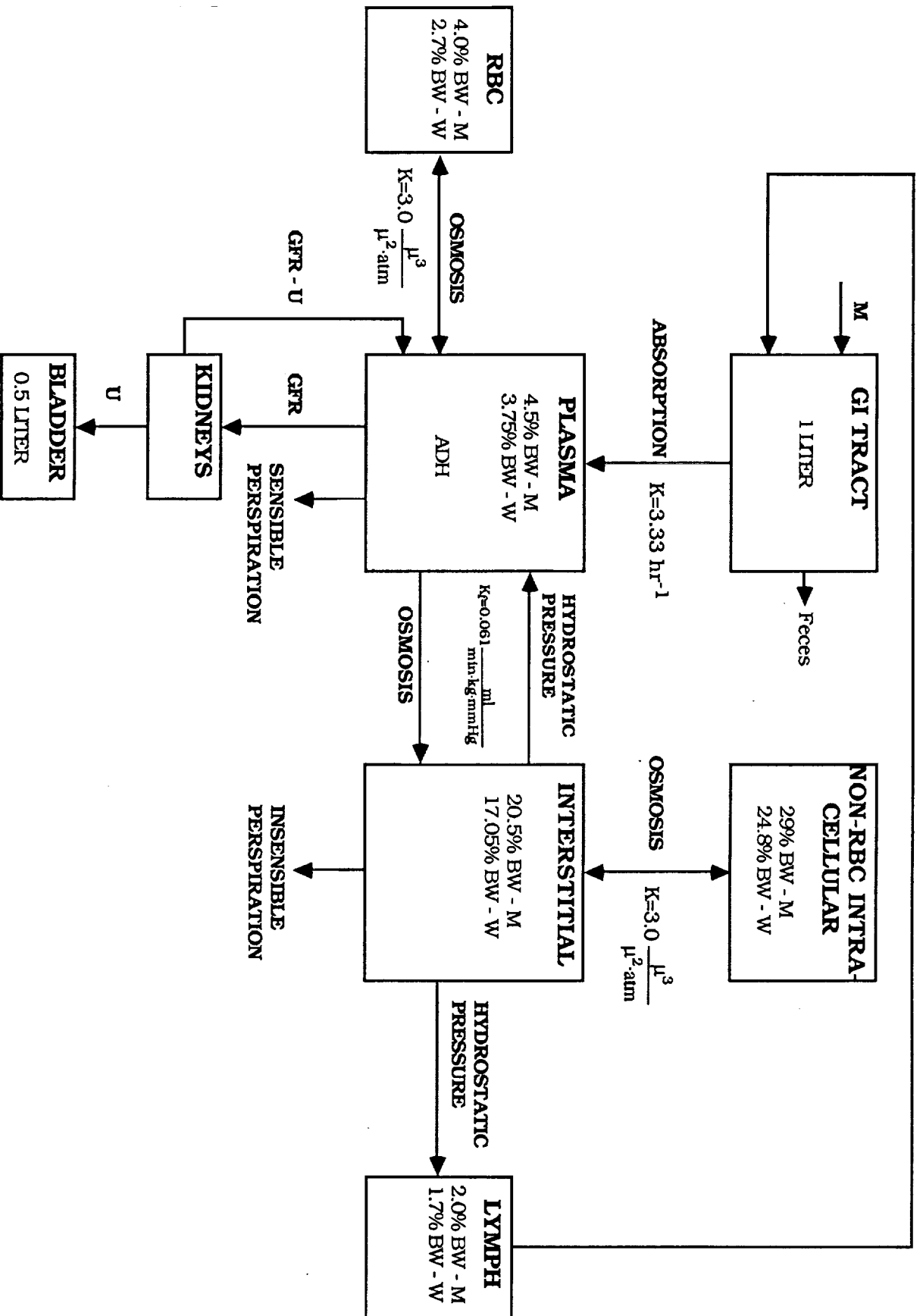


Figure 1: Body water compartments and the forces which cause flow between them. Mass transfer coefficients are represented by  $K$ . The size of each compartment is shown for both males and females where BW = body weight, M = male, & F = female.

## Interactions between Body Water Compartments

Water enters the body through the digestive tract and moves across the mucosa of the small and large intestines in response to osmotic gradients (Ganong, 1991). Previous studies have estimated that water is absorbed from the gastrointestinal tract (GI tract) at a constant rate with a zeroth order rate constant of  $3.3 \text{ hr}^{-1}$  (Reeve & Guyton, 1967). The volume of the stomach, which is given in figure 1, is about one liter (Hole, 1987). Water is also produced by the intracellular metabolism of nutrients. The movement of water between the fluid compartments is controlled by hydrostatic pressure, osmotic pressure, or both.

Fluid movement between the extracellular and intracellular compartments is built on three main points: (1) that water can easily move between the two compartments; (2) that most of the solutes on each side of the cell membrane will not penetrate the membrane easily; and (3) that hydrostatic pressure differences do not play a major role in the final fluid distribution (Coleman, Norman, & Manning *in* Guyton, Taylor, & Granger, 1975). In other words, water will cross the cell membrane until osmotic equilibrium has been attained between the two compartments. Hydrostatic pressures are not a major factor in this osmotic equilibrium since the cell wall is extremely flexible and marked volume changes do not produce significant intracellular hydrostatic pressure (Coleman, Norman, & Manning *in* Guyton, Taylor, & Granger, 1975).

To determine the rate at which water penetrates the cells, the cell membrane permeability and surface area must be known. The hydraulic permeability of the human cell membrane to water is approximately  $3.0 \mu^3 \text{ water}/\mu^2 \cdot \text{atm}$  (West, 1985). The surface area of the red blood cell compartment, which is in osmotic equilibrium with the plasma compartment, can be calculated from the blood volume, hematocrit (Hct), red blood cell volume, and red blood cell surface area. The blood volume can be calculated with the following equation.

$$\text{Blood volume} = \frac{\text{Plasma volume}}{1 - \text{Hct}} \quad (1)$$

The average normal hematocrit is 0.47 for men and 0.42 for women (Ganong, 1991). The volume and surface area of a normal red blood cell are  $9.7 \times 10^{-8} \mu\text{l}$  and  $135 \mu\text{m}^2$ , respectively (West, 1985). The surface area of the non-red blood cell compartment, which is in osmotic equilibrium with the interstitial fluid, can be calculated from the average cell size and the volume of the non-red blood cell compartment. The average cell is roughly cubic with dimensions of  $10 \mu\text{m} \times 10 \mu\text{m} \times 10 \mu\text{m}$  (Martini, 1989).

The exchange of fluid between the plasma and interstitial compartments can be described by what are called Starling forces. This exchange occurs



across the capillary walls and is responsible for supplying cells with oxygen and nutrients while removing cellular wastes. Capillary hydrostatic pressure and interstitial osmotic pressure forces fluid out of the capillaries and into the interstitial spaces. Conversely, the interstitial hydrostatic pressure and the plasma osmotic pressure force fluid back into the capillaries. The composition of the plasma is almost identical to that of the interstitial fluid with the exception of the protein content. Most of the relatively large protein molecules cannot penetrate the capillary wall, therefore, the protein content is substantially higher in the plasma and causes the osmotic effects. The protein osmotic pressure is sometimes referred to as the oncotic pressure. Typically the plasma hydrostatic pressure declines from about 37 mm Hg to 17 mm Hg along the length of the capillary whereas the oncotic pressure and interstitial hydrostatic pressure remain relatively constant at 25 mm Hg and 1 mm Hg, respectively. Consequently, fluid is forced out of the arteriole end of the capillary and fluid is forced into the venous end of the capillary. This situation is shown in figure 3.

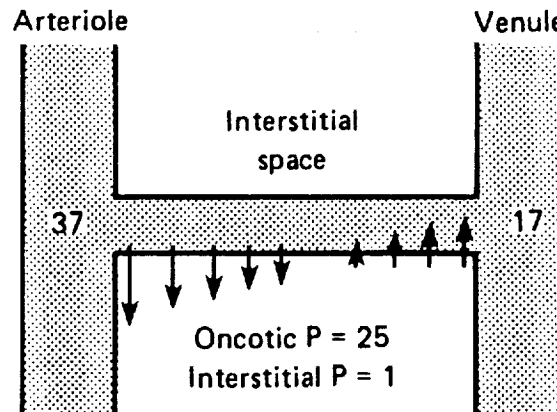


Figure 3: Representation of pressure gradients across the wall of a muscle capillary. The arrows indicate the approximate magnitude and direction of fluid movement. (taken from Ganong, 1991)

Fluid movement is related to the Starling forces through the following expression.

$$\text{Fluid movement} = K_f[(P_c + \pi_i) - (P_i + \pi_c)] \quad (2)$$

where  $K_f$  = capillary filtration coefficient

$P_c$  = capillary hydrostatic pressure

$P_i$  = interstitial hydrostatic pressure

$\pi_c$  = capillary oncotic pressure

$\pi_i$  = interstitial oncotic pressure

For the entire body,  $K_f$  has been found to be approximately 0.061 ml fluid/min·kg body weight·mm Hg (Landis & Pappenheimer, 1963).

During a 24 hour period, about 2 liters more fluid is filtered across the capillary walls than is reabsorbed (Little, 1989). This fluid then flows into the lymphatic system due to a hydrostatic pressure difference. However, since the flow rate of this interstitial fluid and the distance to a lymphatic capillary is extremely small, the pressure gradient between the interstitial spaces and lymphatic capillary is too slight to be measurable (Guyton, Taylor, & Granger, 1975). A primary characteristic of the lymphatic system is that under normal conditions any excess fluid that collects in the tissues is returned back to the circulation (Guyton, 1984). Previous studies have found that the rate of lymph flow can increase up to 20 times the resting level (Guyton, Taylor, & Granger, 1975). This phenomena is mainly due to the structure of the lymphatic capillaries. Endothelial cells of the lymphatic vessels overlap to form pores (see figure 4). As the interstitial space fills with liquid, the tissue swells and the endothelial cells are pulled apart causing the pores to open wider. Therefore, the greater the tissue pressure, the greater the lymph formation rate. The overlapping edges of the endothelial cells also prevent fluid from flowing out of the lymphatic capillary so any compressive force will cause lymph to flow forward through the vessel (Guyton, 1984).

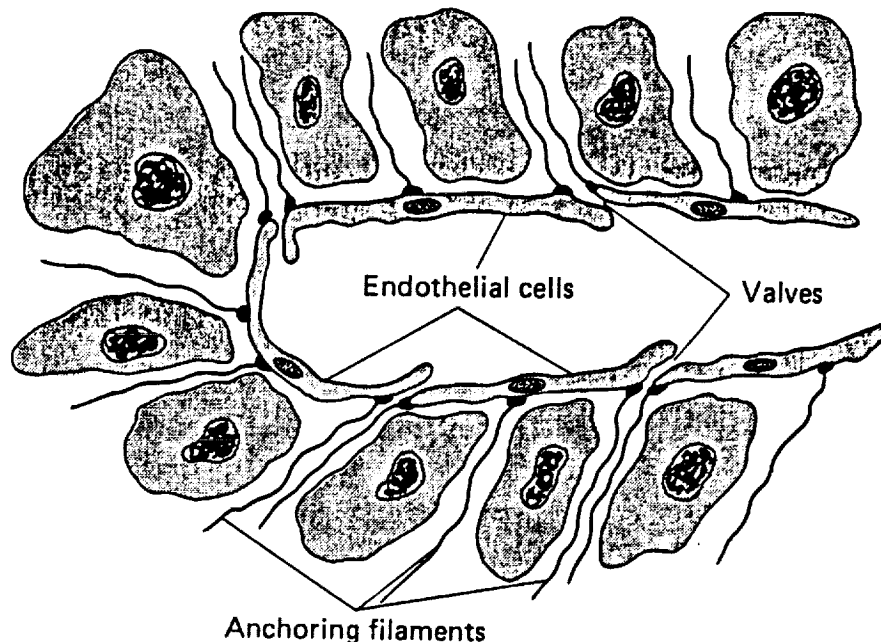


Figure 4: Structure of the lymphatic capillaries which allows for the variable, one directional flow of lymph. (taken from Guyton, 1984)

For the above stated reasons, it is assumed that the lymph flow rate is equal to the net formation of interstitial fluid in figure 1. Figure 5 illustrates the effect of capillary pressure on interstitial fluid pressure, interstitial fluid volume, and lymph flow. From figure 5, it can be seen that the interstitial fluid volume remains relatively constant as the capillary pressure and interstitial pressure are increased until edema, which is an accumulation of fluid in the tissue spaces, occurs. Over this range of capillary pressures, the lymph flow

increases 15 to 20 times normal. Therefore, the lymphatic regulatory system which prevents the buildup of interstitial fluid performs close to its maximum level before edema occurs. Once edema results, the lymphatic system continues to operate at the maximum level thereby alleviating the swelling as quickly as possible.

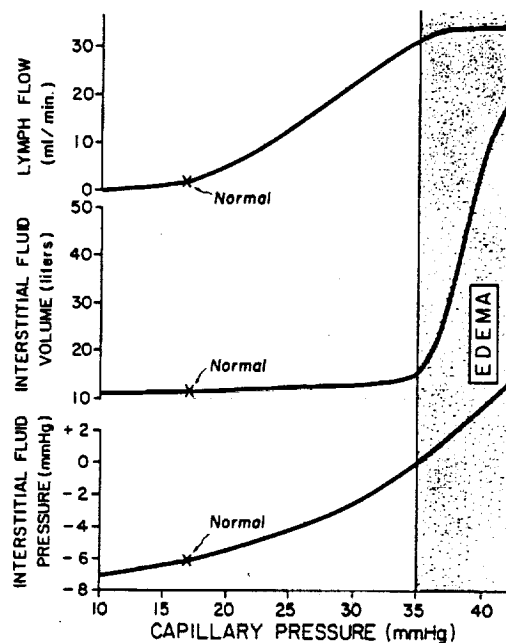


Figure 5: Computed effects of progressive increase in capillary pressure on interstitial fluid pressure, interstitial fluid volume, and lymph flow. (taken from Guyton, Taylor, and Granger, 1975)

## Regulation of Body Water

Water can enter the body as a liquid, with moist food, and as the result of intracellular oxidative metabolism of various nutrients. The primary regulator of water intake is thirst, and although the thirst mechanism is poorly understood, it seems to involve the osmotic pressure of extracellular fluid and a thirst center in the hypothalamus (Hole, 1987).

Water is lost from the body through four routes: sensible perspiration, insensible perspiration, urine, and feces. Water lost by sensible perspiration, or sweating, is a necessary part of the body's temperature control mechanism; water loss in feces accompanies the elimination of undigested food materials; and water losses through diffusion and evaporation (i.e. insensible perspiration) are largely unavoidable (Hole, 1987). Consequently, the only significant route of water loss which can be regulated is the formation of urine. The urine volume, which can vary from less than 1 liter/day to more than 20 liters/day, is determined primarily by the blood pressure and the plasma level of antidiuretic hormone (ADH) (West, 1985). ADH is secreted from the posterior pituitary

gland and the secretion rate is controlled by a center located in the hypothalamus.

The osmolality of the body fluids is regulated by thirst and the renal excretion rate of electrolytes. Ingesting hypotonic liquids will dilute the extracellular water compartment and therefore reduce plasma osmolality. ADH and another hormone, aldosterone, regulate the urinary loss of sodium and potassium.

The thirst center and the ADH secretion rate are stimulated mainly by two physiological conditions, increases in plasma osmolality and decreases in plasma volume (West, 1985). Changes in plasma osmolality are sensed by nerve cells called osmoreceptors located in the hypothalamus. It is believed that the osmoreceptors become reduced in volume by osmotic dehydration when plasma osmolality is elevated, which triggers thirst and ADH release (Cowley *in* Guyton, Taylor, & Grange, 1975). Changes in plasma volume are sensed by stretch receptors located in the heart and blood vessels and by the juxtaglomerular apparatus of the kidney. The stretch receptors are stimulated by distention and their afferent nerve fibers pass via the glossopharyngeal and vagus nerves to the medulla (Ganong, 1991). The juxtaglomerular apparatus secretes an enzyme, renin, in response to a decreased blood volume or decreased blood pressure. Renin converts a circulating blood protein which is produced by the liver, angiotensinogen, to angiotensin I. Angiotensin I is then converted in the lungs to angiotensin II. The actions of angiotensin II include vasoconstriction, which elevates the blood pressure, increased secretion rates of aldosterone and ADH, and stimulation of the thirst center. A change in plasma osmolality of 1% doubles the plasma level of ADH, and the thirst center is stimulated when the plasma osmolality changes 1 to 2%, whereas the change in blood volume necessary to cause these responses is on the order of 10 to 15% (Cowley *in* Guyton, Taylor, and Granger, 1975). However, if the osmoreceptors and volume receptors provide conflicting information, for example a low blood volume with a low osmolality, the volume regulating mechanism will be the only observed mechanism. In other words, volume overrides tonicity. Since the stretch receptors adapt to abnormal blood volumes over a period of several days, and the osmoreceptors do not adapt to abnormal plasma osmolalities (Cowley *in* Guyton, Taylor, and Granger, 1975), the volume regulating mechanism is valid only when considering short term regulation. The osmolality mechanism will be valid for both short term and long term body water regulation. The effect of plasma osmolality and volume on the circulating levels of ADH are shown in figure 6. The relationship between the intensity of thirst and the plasma osmolality is shown in figure 7.

An increase in arterial pressure increases the amount of fluid the kidneys withdraw from the vascular compartment and hence increases the urine flow rate. The relationship between renal arterial pressure and urine production is shown in figure 14 and will be discussed in the following section.

## Description of the kidney

The urinary system includes the kidneys, ureters, bladder, and urethra. The function of this system is to maintain homeostasis of the body fluids by adjusting the composition of circulating blood. The kidneys receive about 25%

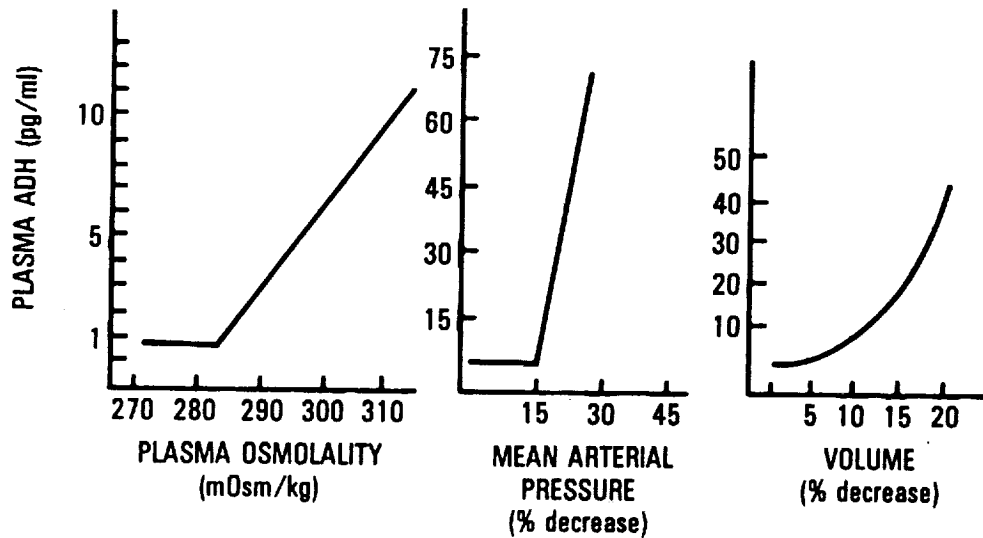


Figure 6: Control of plasma ADH concentration by osmolality, mean arterial pressure, and circulatory volume. (taken from West, 1985)

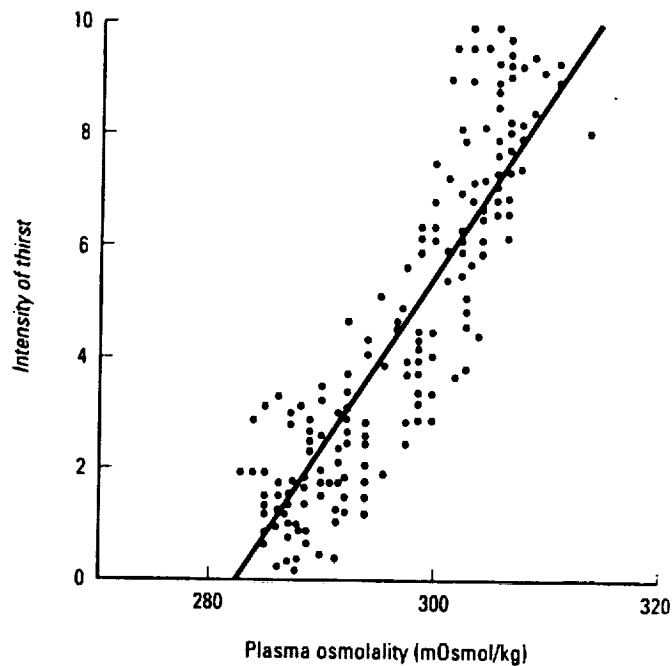


Figure 7: Relation of plasma osmolality to thirst in healthy adult humans during infusion of hypertonic saline. The intensity of thirst is measured on a special analog scale. (taken from Ganong, 1991)

of the cardiac output and filters out a fluid similar to plasma. The composition of this filtered fluid changes as it flows through the kidney tubules since compounds are continually being secreted and reabsorbed. Ultimately, the plasma-like fluid becomes urine. Through this mechanism, the kidneys eliminate wastes while conserving body water, electrolytes, and metabolites.

The kidneys are shaped similar to lima beans and weigh about 300 grams apiece. The internal structure of the kidney can be divided into two parts, an outer portion called the cortex and an inner portion called the medulla (see figure 8). The medulla of each kidney contains 6-18 conical renal pyramids, whose tips, or papillae, are each surrounded by a minor calyx (Martini, 1989). Several minor calyces combine to form a major calyx and the major calyces join within the renal pelvis which is connected to a ureter.

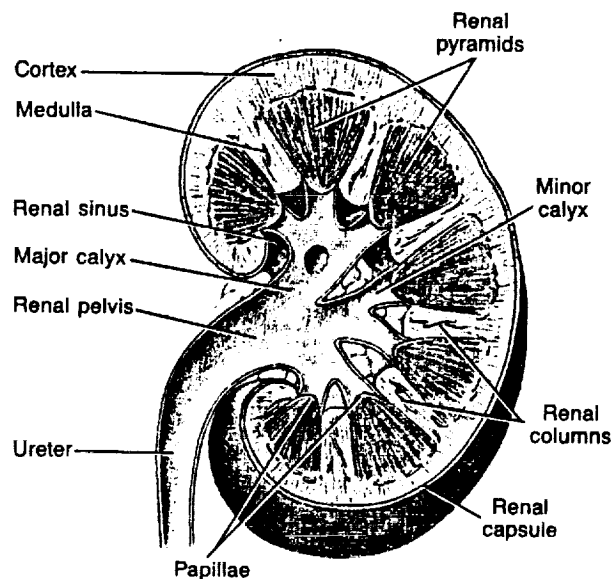


Figure 8: Gross anatomy of the right kidney, in sectional view. (taken from Martini, 1989)

The nephron is the functional unit of the kidney and consists of a renal tubule and an expanded end or Bowman's capsule (see figure 9). Each human kidney contains about 1.3 million nephrons. The Bowman's capsule surrounds a capillary bed, the glomerulus, which receives blood through an afferent arteriole and discharges blood, less some filtrate, through an efferent arteriole. Fluid must penetrate three layers, the fenestrated capillary endothelium, the basement membrane which surrounds the capillary wall, and the glomerular epithelium, before it can enter the capsular space (see figure 10). The structure of these membranes allow water and other small molecules to cross easily but restricts the passage of larger molecules such as plasma proteins. The forces which control the filtration of plasma fluid into the Bowman's capsule include the capillary hydrostatic pressure and capsular oncotic pressure, which force

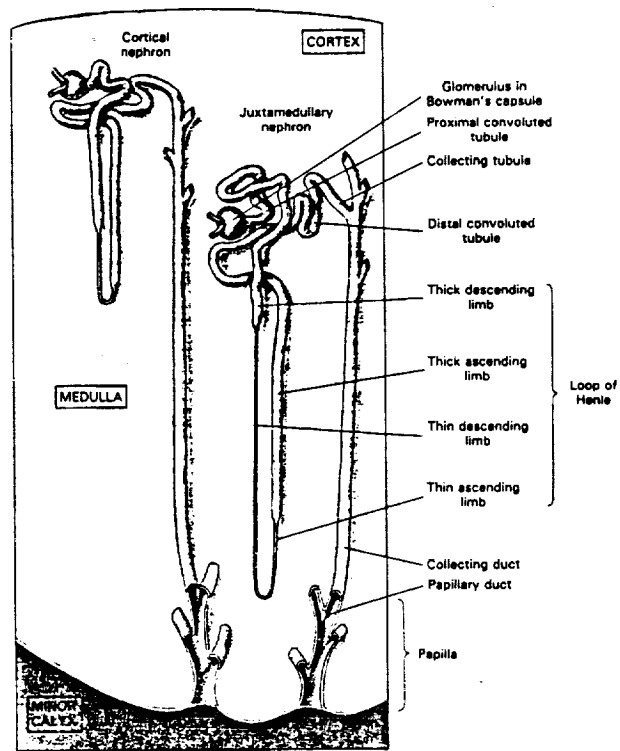


Figure 9: The functional nephron. (taken from Martini, 1989)

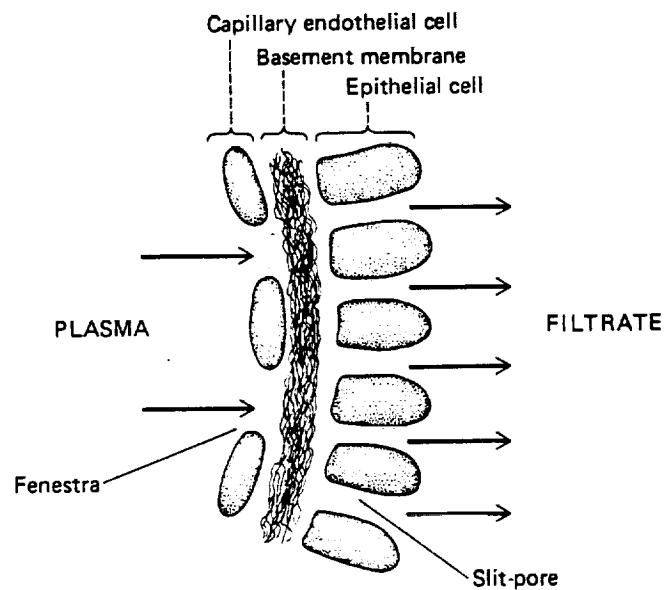


Figure 10: Functional structure of the glomerular membrane. (taken from Guyton, 1984)

fluid into the capsular space, and the plasma oncotic pressure and capsular hydrostatic pressure, which force fluid into the capillaries. The renal capillary pressure is normally 60 mm Hg, whereas the colloid pressure in the glomerulus is normally 32 mm Hg (Guyton, 1984). The pressure in Bowman's capsule is about 18 mm Hg, and the colloid osmotic pressure in the capsule is essentially zero (Guyton, 1984). The capillary hydrostatic pressure may be varied considerably by the constriction of the afferent or efferent arterioles. The rate at which filtrate enters the capsule is called the glomerular filtration rate (GFR). Typically, 180 liters of fluid enter the renal tubules each day although only about one liter of urine is produced due to the secretion and reabsorption processes which occur along the length of the nephron.

The glomerular filtrate passes from the capsular space into the proximal convoluted tubule due to a hydrostatic pressure gradient. Simple cuboidal epithelial cells with microvilli line this portion of the nephron. The function of the proximal tubule is to actively reabsorb electrolytes and nutrients from the filtered fluid. As these solutes are absorbed, water flows into the epithelial cells and eventually into the interstitial fluid by osmosis. Consequently, the tubular fluid remains isotonic with respect to plasma as it travels through the proximal tubule. By the time the tubular fluid reaches the next segment of the nephron, the loop of Henle, 60 - 70% of the filtered solute and water have been removed (Ganong, 1991).

From figure 9, it can be seen that the loop of Henle consists of a descending limb and an ascending limb, each of which have thin and thick segments. The length of the loop Henle depends upon the location of the nephron within the kidney. Nephrons in the outer portions of the kidney, or cortical nephrons, have short loops whereas nephrons closer to the medulla, or juxtamedullary nephrons, have longer loops. For the juxtamedullary nephrons, a concentration gradient exists within the interstitial fluid along the length of the loop of Henle. The variation of osmolality within the medulla is shown in figure 11.

The descending limb of Henle, which is composed mainly of the thin segment, is freely permeable to water and relatively impermeable to ions (Martini, 1989). Since the osmolality of the interstitial fluid increases with depth into the medulla, water is reabsorbed from this segment by osmosis. The ascending thin limb of Henle is impermeable to water and permeable to sodium. The ascending thick limb is also impermeable to water and actively reabsorbs sodium. Since the rate of active transport is proportional to the concentration, more sodium is reabsorbed in the deeper portion of the ascending limb than in the superficial portion of the ascending limb. This active transport aids in maintaining the osmotic gradient within the medullary interstitial fluid. By the time the tubular fluid reaches the next portion of the nephron, the distal convoluted tubule, the osmolality has fallen to 100 mosm.



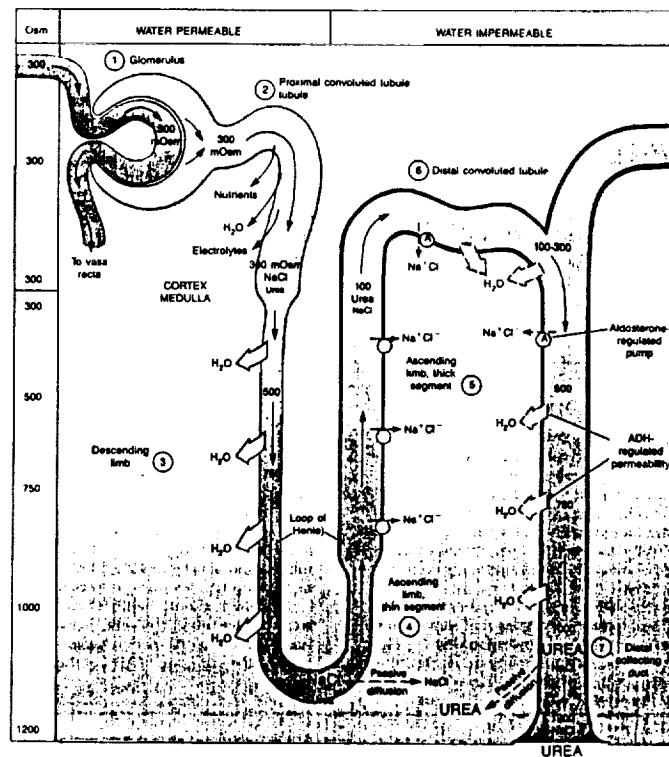


Figure 11: An overview of kidney function. (taken from Martini, 1989)

Near the portion of the nephron where the afferent and efferent arterioles permeate the Bowman's capsule, the ascending limb of Henle ends and forms a tight bend that places a portion of the distal tubule in direct contact with the arterioles (see figure 12). The cells of the distal tubule which contact the arterioles are known as the macula densa, and the associated smooth muscle cells in the wall of the afferent arteriole are called the juxtaglomerular cells. Together, the macula densa and the juxtaglomerular cells make up the juxtaglomerular apparatus, a secretory complex which releases renin and erythropoietin in response to a lowered blood pressure. Renin converts circulating angiotensinogen to angiotensin I which is converted to angiotensin II, a powerful vasoconstrictor, in the lung capillaries. Angiotensin II also increases the secretion rates of ADH and aldosterone. The renin-angiotensin system is shown in figure 13. Erythropoietin stimulates the formation of red blood cells in the bone marrow and therefore maintains or in some cases increases the oxygen carrying capacity of the blood.

The distal convoluted tubule, collecting tubule, and collecting duct are essentially impermeable to water unless ADH is present in the body fluids. ADH in the interstitial kidney fluid binds to receptors located in the basal membranes of cells in these portions of the nephron (see figure 14). This coupling of receptor and ADH activates adenyl cyclase, an enzyme associated with the cell membrane, which catalyzes the production of cyclic adenosine monophosphate (cyclic AMP) (Sullivan, 1982). It is the increased cyclic AMP concentration within the cell that increases the permeability of the apical membrane, however, the mechanism by which the permeability changes is not well established. In high concentrations, ADH increases the amount of water absorbed in these nephron segments, thereby causing the formation of a

concentrated urine. Conversely, in the absence of ADH, large amounts of a dilute urine will be formed.

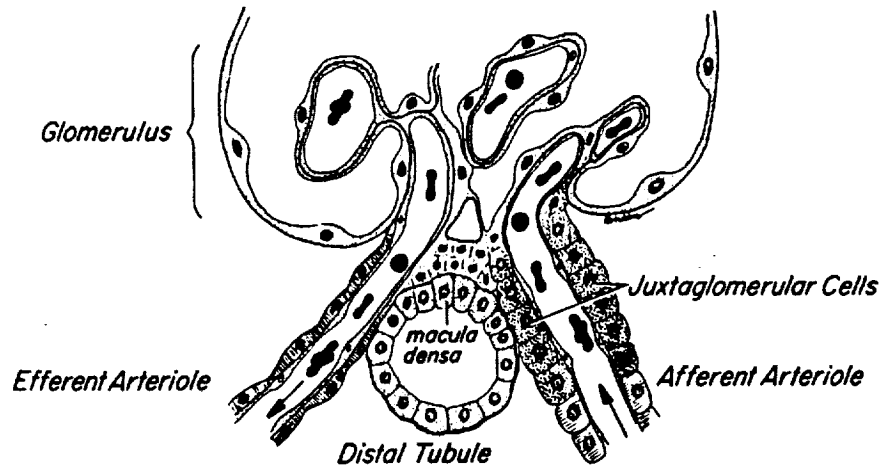


Figure 12: The juxtaglomerular apparatus. (taken from Brown & Stubbs, 1983)

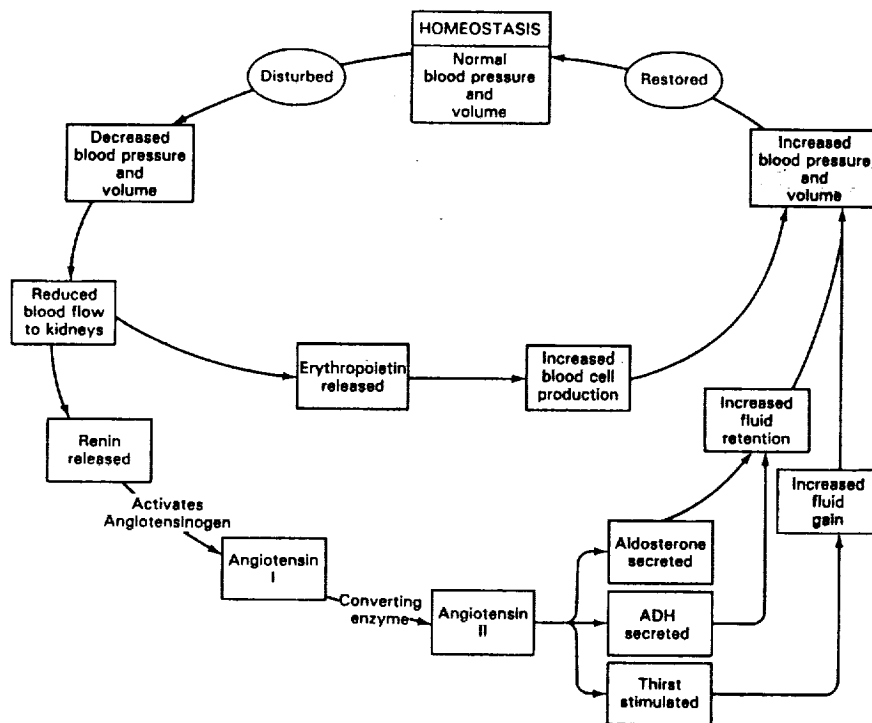


Figure 13: The renin-angiotensin system. (taken from Martini, 1989)

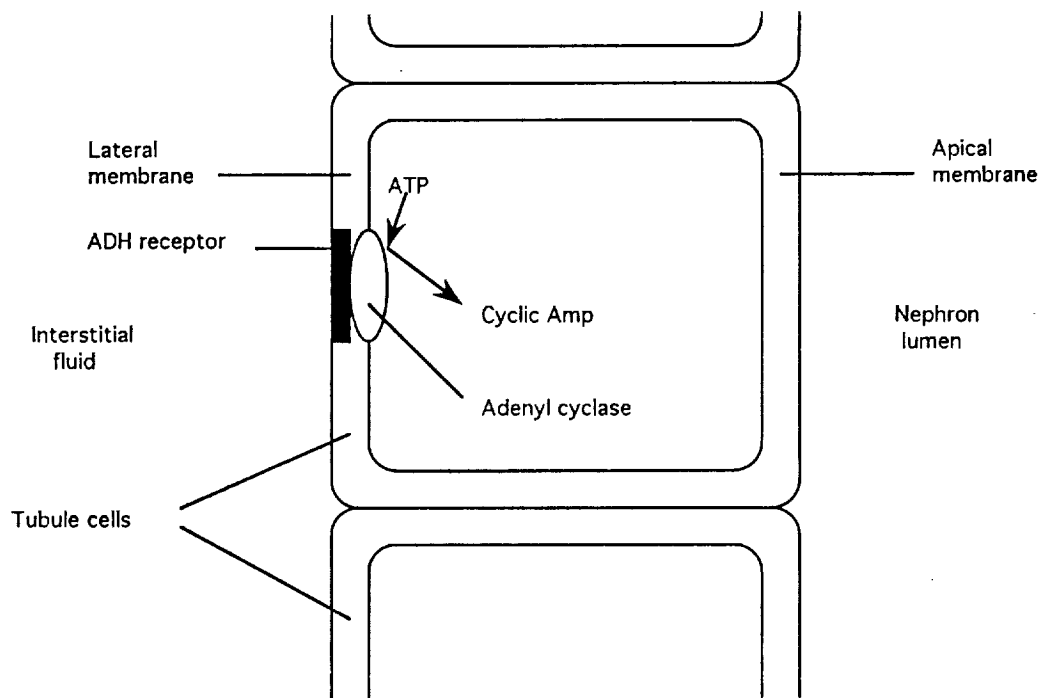


Figure 14: The binding of ADH to cells of the distal tubule and collecting duct.

The reabsorption of sodium from the tubular fluid within the distal convoluted tubule, collecting tubule, and collecting duct is controlled by the hormone aldosterone, which is secreted from the adrenal gland when plasma levels of angiotensin II or potassium are elevated. Aldosterone stimulates ion pumps in these portions of the nephron, which then exchange sodium ions for potassium ions. Therefore, aldosterone increases the urinary loss of potassium while reducing this loss of sodium.

Sodium accounts for over 90% of the cations in the extracellular fluid (Guyton, 1984). Due to electroneutrality of the extracellular fluid, the amount of cations automatically controls the number of anions present, so by regulating the concentration of sodium, over 90% of the ions are also controlled. Since the ions account for most of the dissolved species in the bodily fluids, the concentration of sodium is directly related to the fluid osmolality. Therefore, in terms of regulating the body fluid compartments, the renal handling of water and sodium will be the most important factors to consider when modeling kidney function.

In regulating the body fluid compartments, volume is controlled primarily by the arterial pressure, sodium concentration primarily by anti-diuretic hormone, and potassium levels primarily by aldosterone (Guyton & Young in Guyton, Taylor, and Granger, 1975). Increasing the arterial pressure slightly increases renal blood flow and the glomerular filtration rate, however, the urine flow rate can be greatly increased. Furthermore, urine production may cease altogether if the arterial pressure falls below 60 mm Hg. The variation of renal

blood flow, GFR, and urine flow is shown as a function of arterial pressure in figure 15. Therefore, a depleted blood volume, which causes a drop in blood pressure, will decrease urine flow and tend to alleviate the problem. Alternatively, an expanded blood volume, which causes an elevated blood pressure, will increase the urine flow rate thereby decreasing the blood volume.

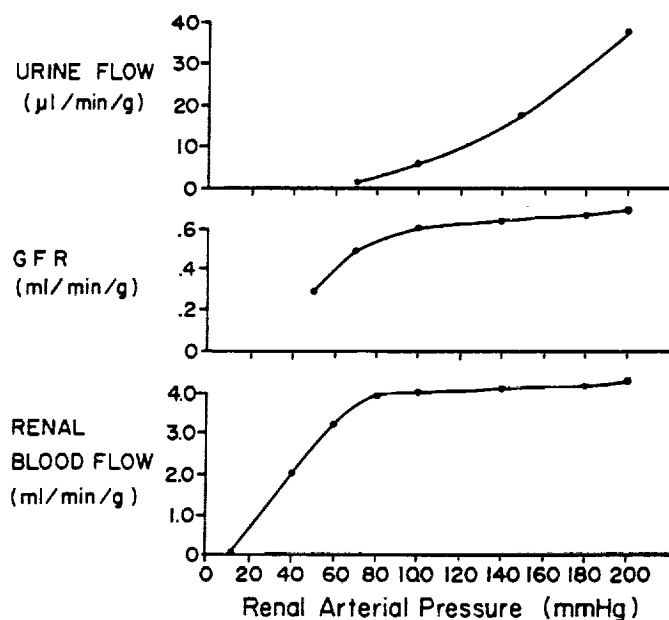


Figure 15: Effect of acute changes in arterial pressure on the important hemodynamic variables of renal function that relate to renal volume excretion. (taken from Navar & Guyton in Guyton, Taylor, & Granger, 1975)

The secretion rate of ADH and the thirst center response are strongly related to the plasma osmolality. A change in plasma osmolality of 1% doubles the plasma level of ADH and the thirst center is stimulated when the plasma osmolality changes 1 to 2% (Cowley in Guyton, Taylor, and Granger, 1975). An elevated plasma level of ADH is usually believed to increase the blood volume by reducing the urinary water loss and increasing the amount of water ingested. Increasing the plasma ADH level initially will increase in the blood volume but only to a small extent because of the associated increase in arterial pressure and urine flow rate (see figure 15) and the urine which is formed, will have a high solute to water ratio. Consequently, persistently high levels of ADH will cause a slight increase in the blood volume but will also decrease the plasma osmolality due to a high flow rate of concentrated urine. Since sodium is responsible for about 95% of the plasma osmolality, ADH primarily affects the sodium concentration of the extracellular fluid.

Aldosterone causes cells in the later portion of the nephron to absorb sodium from the tubular fluid with the simultaneous secretion of potassium. It would therefore be expected that aldosterone would control the sodium and

potassium levels in the extracellular fluid. However, previous studies have found that aldosterone plays about ten times as much role in the control of potassium concentration as in the control of sodium ion concentration (Guyton & Young in Guyton, Taylor, and Granger, 1975). The reason for this is that the ADH-thirst mechanism is a very potent mechanism for control of sodium ion concentration, so potent that the aldosterone mechanism, in competing with this more potent mechanism, is indeed a very poor competitor (Guyton & Young in Guyton, Taylor, and Granger, 1975).

## Modeling Kidney Function

Since sodium accounts for over 90% of the cations in the extracellular fluid, and the number of cations is balanced by the number of anions, considering the renal handling sodium and water only should sufficiently describe the relationship between the plasma compartment and kidneys. The following model has been adapted from a previous model of normal renal function in man (Uttamsingh, Leaning, Bushman, Carson, & Finkelstein, 1985).

### *Cardiovascular system*

The cardiovascular system consists of a pump, the heart, an assortment of conducting channels, the vessels, and a flowing fluid, the blood. These components are illustrated in figure 16. Arteries carry blood away from the heart and veins return blood to the heart. The blood vessels, which make up the circulatory system, can be sub-divided into two parts. Pulmonary vessels bring blood to and from the lungs whereas systemic vessels service the rest of the body.

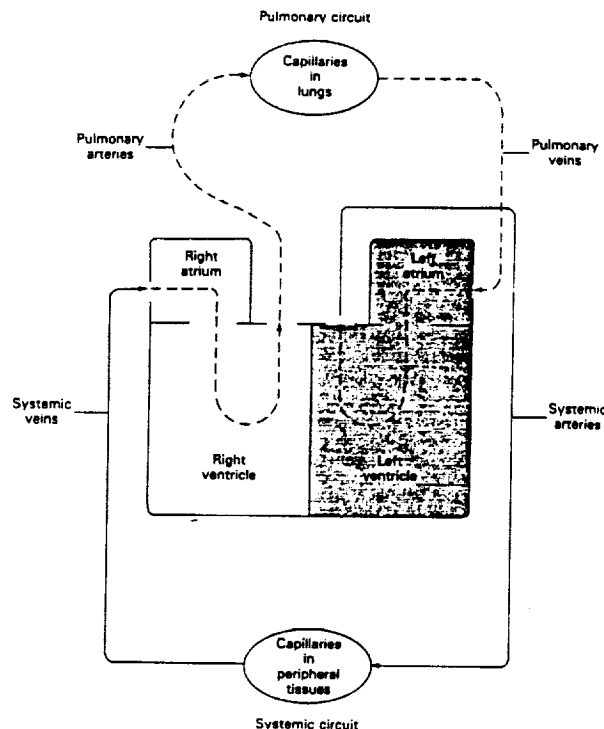


Figure 16: The cardiovascular system. (taken from Martini, 1989)

Blood pressure, which affects the glomerular filtration rate, is directly related to the blood volume. An increased blood volume increases the cardiac output and consequently the blood pressure. Additionally, an increased blood volume stretches elastic fibers located in the vessel walls which causes the fibers to contract more powerfully and elevate the blood pressure. A decreased blood volume causes the opposite effects. The experimental relationship between the blood volume, BV, and the mean systemic pressure, MSP, can be described by

$$MSP = 3.5(BV - 3) \quad (3)$$

where the mean systemic pressure is the average pressure within the blood vessels from the root of the aorta to the end of the great veins (Uttamsingh, Leaning, Bushman, Carson, & Finkelstein, 1985).

CO = Since angiotensin II is a powerful vasoconstrictor, it will influence the peripheral resistance which is the resistance to blood flow caused by friction with the vessel walls. Short term, neural control of vascular tone is neglected in this model. The relationship between the resistance of the entire circulatory system, or total peripheral resistance (TPR), and the plasma level of angiotensin II (A) can be approximated for humans by the following equations (Uttamsingh, Leaning, Bushman, Carson, & Finkelstein, 1985).

$$TPR = 19 + 0.037A \quad \text{for } A \leq 27 \frac{\text{ng}}{\text{l}} \quad (4)$$

$$TPR = 12.2 + 5.44 \log(A) \quad \text{for } A > 27 \frac{\text{ng}}{\text{l}} \quad (5)$$

Cardiac output, CO, increases with oxygen consumption which is primarily determined by the metabolic rate. The relationship between cardiac output and oxygen consumption is approximately linear (McArdle, Katch, & Katch, 1986) and is shown in figure 17. This will be described more in detail when increased levels of activity are included in the model. At rest the cardiac output is about 5 liters/min.

Blood flow through vessels can be described by the following relationship.

$$\text{Blood flow} = \frac{[\text{Pressure (upstream)} - \text{Pressure (downstream)}]}{\text{Resistance}} \quad (6)$$

The arterial pressure (AP) can be solved for from equation 6.

$$AP = CO(TPR) \quad (7)$$

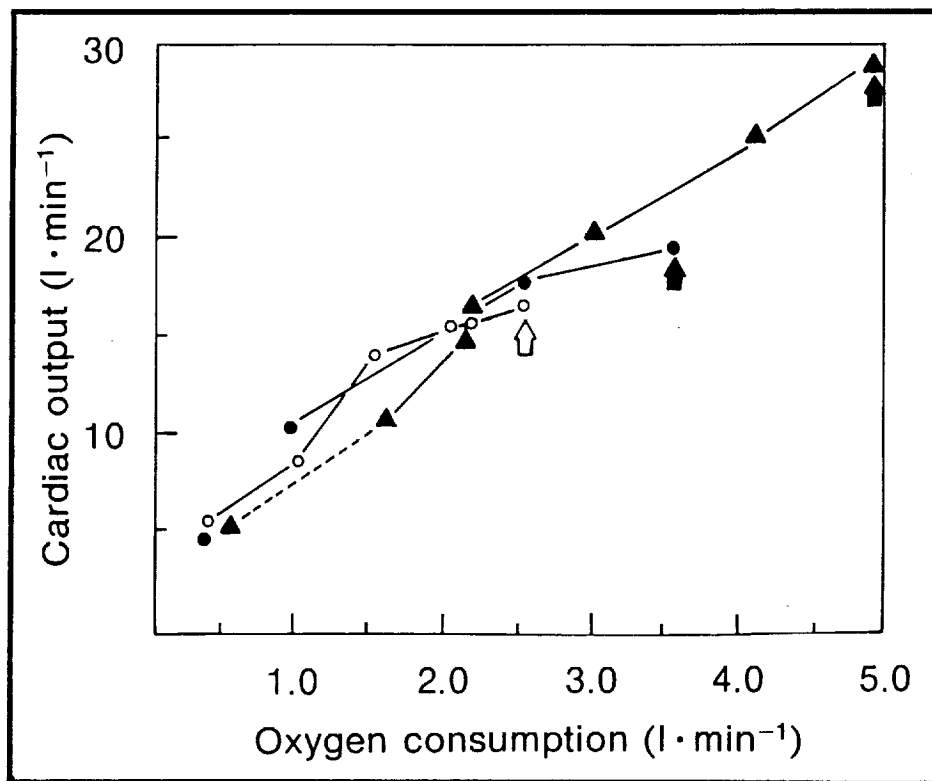


Figure 17: Cardiac output in relation to oxygen consumption during upright exercise in endurance athletes (solid triangles) and sedentary college students prior to (hollow circles) and following (solid circles) 55 days of aerobic training. Arrows represent maximum oxygen consumption for each category. (taken from McArdle, Katch, & Katch, 1986)

### Renal function

**Glomerular function** The forces which control the filtration of plasma fluid into the Bowman's capsule include the capillary hydrostatic pressure and capsular oncotic pressure, which force fluid into the capsular space, and the plasma oncotic pressure and capsular hydrostatic pressure, which force fluid into the arterioles. These latter three pressures remain relatively constant under normal physiological conditions, therefore, the glomerular filtration rate will depend mainly upon the pressure within the arterioles. The following relationship between the arterial pressure and glomerular filtration rate has been previously determined (Goldstein & Rypins, 1992).

$$\text{GFR} = 4.50 - 1.62\text{AP} + 0.100(\text{AP})^2 - 1.2 \times 10^{-3}(\text{AP})^3 + 5.73 \times 10^{-6}(\text{AP})^4 - 9.89 \times 10^{-9}(\text{AP})^5 \quad (8)$$

Chemical analysis of glomerular filtrate has found that it has approximately the same sodium concentration as plasma (Lote, 1987) so the rate of filtration of sodium into the proximal tubule (FNa) is given by

$$FNa = GFR(PNa) \quad (9)$$

Proximal tubule Electrolytes are actively reabsorbed in this portion of the nephron therefore the rate of sodium reabsorption (SPTR) can be described by a mass transfer coefficient multiplied by the sodium concentration of the tubular fluid.

$$SPTR = GTB(FNa) \quad (10)$$

where GTB is the glomerular tubular balance or mass transfer coefficient. This coefficient is known to be a function of the sodium concentration of the tubular fluid. Since the concentration of sodium in the proximal tubule is nearly equal to the concentration of sodium in the plasma (PNa), the following linear relationship has been previously derived as a first-order approximation (Uttamsingh, Leaning, Bushman, Carson, & Finkelstein, 1985).

$$GTB = 5.815 - 0.0357PNa \quad (11)$$

As electrolytes are pumped out of this portion of the tubule, water follows by osmosis. Since sodium makes up the majority of the cations in the filtered fluid, and as sodium is removed from tubule negatively charged ions follow due to an electrical gradient, the fraction of water reabsorbed in the proximal tubule will be nearly equal to the fraction of sodium reabsorbed.

$$EPTR = GTB(GFR) \quad (12)$$

where EPTR is the rate of water reabsorption in the proximal tubule. From equations 10 and 12, the flow rates of sodium (SFLH) and water (EFLH) into the loop of Henle can be determined.

$$SFLH = FNa - SPTR \quad (13)$$

$$EFLH = GFR - EPTR \quad (14)$$

Loop of Henle Examinations of the reabsorptive characteristics of sodium and water for the entire loop have demonstrated that the fraction of water reabsorbed (EBLH) is a function of transit time, or an inverse function of flow rate, whereas the fraction of sodium reabsorbed remains fairly constant with flow rate. The following relationships for the rate of reabsorption of sodium (SLHR) and water (ELHR) have been derived for this portion of the nephron (Uttamsingh, Leaning, Bushman, Carson, & Finkelstein, 1985).

$$EBLH = -0.01EFLH + 0.65 \quad (15)$$



$$ELHR = EBLH(EFLH) \quad (16)$$

$$SLHR = 0.8SFLH \quad (17)$$

The flow rate of water (EFDT) and sodium (SFDT) into the distal tubules is given by

$$EFDT = EFLH - ELHR \quad (18)$$

$$SFDT = SFLH - SLHR \quad (19)$$

Distal and collecting tubules In these portions of the nephron, the amount of water reabsorbed is controlled by antidiuretic hormone (ADH) and the amount of sodium reabsorbed by aldosterone (ALD). Using data from previous experiments, relationships for the rate of water reabsorbed (EDTR) and the rate of sodium reabsorbed (SDTR) have been derived (Goldstein & Rypins, 1992).

$$EDTR = EFDT[0.0417 - 0.400ADH + 0.637(ADH)^2 - 0.222(ADH)^3 + 0.0345(ADH)^4 - 0.00254(ADH)^5 + 7.25 \times 10^{-5}(ADH)^6] \quad (20)$$

$$SDTR = SFDT [ 0.572 + 0.00195(ALD) + 5.15 \times 10^{-5}(ALD)^2 - 7.98 \times 10^{-7}(ALD)^3 + 4.93 \times 10^{-9}(ALD)^4 - 1.69 \times 10^{-11}(ALD)^5 + 3.52 \times 10^{-14}(ALD)^6 - 4.56 \times 10^{-17}(ALD)^7 + 3.61 \times 10^{-20}(ALD)^8 - 1.59 \times 10^{-23}(ALD)^9 + 3.02 \times 10^{-27}(ALD)^{10} ] \quad (21)$$

Urine flow (UFL) is then given by

$$UFL = EFDT - EDTR \quad (22)$$

and the urinary excretion rate of sodium (UNa) is given by

$$UNa = SFDT - SDTR \quad (23)$$

Note that these equation predict that ADH can produce large percentage changes in fluid reabsorption whereas aldosterone has only a small modulating effect on sodium reabsorption. This agrees with the discussion at the end of the previous section (Description of the kidney) which stated that ADH is the primary controller of sodium in the extracellular fluid and the urinary sodium excretion rate. However, a full analysis requires the inclusion of aldosterone.

### *Hormonal systems*

Having derived equations for the reabsorption of sodium and water in the latter portions of the nephron, which depend upon ADH and aldosterone, the levels of these hormones must now be estimated.

Control of ADH concentration Plasma ADH concentration is determined by three factors: the rate of ADH release from the posterior pituitary gland which depends upon signals from osmoreceptors and stretch receptors, the rate of clearance of ADH from the body by the liver and kidneys, and the volume in which the ADH is dispersed. As seen in figure 6, plasma ADH levels, and consequently the ADH release rate, increase as plasma osmolality increases and blood volume decreases. Equations for ADH release as a function of plasma osmolality (ADHSP) (DeHaven & Shapiro, 1970) and extracellular compartment volume (ADHSV) (Uttamsingh, Leaning, Bushman, Carson, & Finkelstein, 1985) have been derived from experimental data.

$$\text{ADHSP} = 0.833\text{PNa} - 117.45 \quad \text{for PNa} \geq 141.9 \text{ mosm/l} \quad (24)$$

$$\text{ADHSP} = 0.06\text{PNa} - 7.83 \quad \text{for PNa} < 141.9 \text{ mosm/l} \quad (25)$$

$$\text{ADHSV} = 0.0 \quad \text{for DWV} \geq 1.8 \quad (26)$$

$$\text{ADHSV} = 0.15 - 0.083\text{DWV} \quad \text{for } 1.8 > \text{DWV} \geq 1.0 \quad (27)$$

$$\text{ADHSV} = 0.813 - 0.75\text{DWV} \quad \text{for } 1.0 > \text{DWV} \geq -1.2 \quad (28)$$

$$\text{ADHSV} = 1.71 \quad \text{for } -1.2 > \text{DWV} \quad (29)$$

where DWV is the deviation of the extracellular compartment volume (E) from the normal value ( $E_N$ ).

$$\text{DWV} = E - E_N \quad (30)$$

The signals for ADH release in response to variations in plasma osmolality and blood volume are additive if both signals tend to increase the ADH release rate (ie. increased plasma osmolality with decreased blood volume). However, if both the plasma osmolality and blood volume are above normal, the signal for blood volume will be the primary signal. Recall that volume overrides tonicity. For this case the net rate of ADH (ADHS) release is given by the following equations (Uttamsingh, Leaning, Bushman, Carson, & Finkelstein, 1985).

$$\text{ADHS} = \frac{17.0(\text{DWV})(\text{ADHSV}) + \text{ADHSP}}{17.0(\text{DWV}) + 1.0} \quad (31)$$

for POS > 299.6 mosm/l and DWV > 2.0

$$\text{ADHS} = \frac{[33.0(\text{DWV}) - 32.0]\text{ADHSV} + \text{ADHSP}}{33.0(\text{DWV}) - 31.0} \quad (32)$$

for POS > 299.6 mosm/l and  $1.0 \leq \text{DWV} \leq 2.0$

For all other cases

$$ADHS = \frac{ADHSV + ADHSP}{2.0} \quad (33)$$

The rate of clearance of ADH from the plasma (DADH) has been found to be related to the plasma concentration of ADH (Uttamsingh, Leaning, Bushman, Carson, & Finkelstein, 1985).

$$DADH = 0.206 \quad \text{for ADH} > 4.0 \text{ munits/l} \quad (34)$$

$$DADH = 0.374 - 0.042 \text{ ADH} \quad \text{for ADH} \leq 4.0 \text{ munits/l} \quad (35)$$

where the clearance rate of a substance is defined as the amount of blood completely cleared of the substance per unit time. For example, a clearance rate for ADH of 0.206 l/min means that ADH is completely removed from 0.206 liters of blood every minute.

Previous studies have found that ADH is confined mainly to the plasma compartment, therefore, the volume that ADH is distributed into is equal to the plasma volume (PV) (Uttamsingh, Leaning, Bushman, Carson, & Finkelstein, 1985). A material balance on ADH yields

$$(PV) \frac{d(ADH)}{dt} = ADHS - DADH(ADH) \quad (36)$$

Control of aldosterone concentration Aldosterone release is one of the final consequences of the renin/angiotensin system, the function of which is to provide feedback control on the rates of sodium and potassium excretion, and thereby influence the volume of the extracellular and intracellular compartments (see figure 13). In absence of more explicit data, a linear relationship has been postulated for the rate of renin release (RS) as a function of the amount of sodium entering the distal tubule (Uttamsingh, Leaning, Bushman, Carson, & Finkelstein, 1985).

$$RS = 0.0163 - 0.0093SFD T \quad (37)$$

This equation is consistent with the fact that the macula densa, which secretes renin into the plasma compartment, monitors fluid within the distal tubule. Renin is removed from the circulation on passage through the liver with a clearance rate of approximately 0.135 l/min (Uttamsingh, Leaning, Bushman, Carson, & Finkelstein, 1985). A material balance on renin yields

$$(PV) \frac{dR}{dt} = RS - 0.135R \quad (38)$$

where R is the plasma concentration of renin.

Renin catalyses the reaction which converts circulating angiotensinogen to angiotensin I. Angiotensin I is rapidly converted to angiotensin II by enzymes

in the lungs. The following equation has been derived for the rate of formation of angiotensin II (AS) (Uttamsingh, Leaning, Bushman, Carson, & Finkelstein, 1985).

$$AS = 583.3R(PV) \quad (39)$$

The rate of clearance of angiotensin II from the plasma has been found to be approximately 4.04 l/min (Uttamsingh, Leaning, Bushman, Carson, & Finkelstein, 1985). A material balance on angiotensin II yields

$$(PV) \frac{dA}{dt} = AS - 4.04A \quad (40)$$

The major factor which regulates the release of aldosterone from the adrenal gland is the plasma concentration of angiotensin II. From previous animal studies, the following relationships for the rate of aldosterone release (ALS) as a function of plasma angiotensin II concentration have been derived (Uttamsingh, Leaning, Bushman, Carson, & Finkelstein, 1985).

$$ALS = 0.75A + 7.76 \quad \text{for } A < 18 \text{ ng/l} \quad (41)$$

$$ALS = 3.32A - 38.5 \quad \text{for } 18 \leq A < 34.0 \quad (42)$$

$$ALS = 0.585A + 54.6 \quad \text{for } A \geq 34.0 \quad (43)$$

The clearance rate of aldosterone from the plasma has been found to be approximately 0.62 l/min (Uttamsingh, Leaning, Bushman, Carson, & Finkelstein, 1985) which leads to the following material balance.

$$(PV) \frac{dALD}{dt} = ALS - 0.62ALD \quad (44)$$

Sodium and potassium balance Since the overall model of the body water compartments is concerned mainly with water and sodium, recall that sodium ions account for almost 95% of the cations in the extracellular fluid, the present model will assume that the extracellular potassium concentration remains constant at a typical value of 4 meq/l. The timed average daily ingestion rate of sodium (SODMIN) and the urinary excretion rate of sodium (UNa) will determine the amount of sodium in the extracellular fluid (TENA).

$$\frac{d(TENA)}{dt} = SODMIN - UNa \quad (45)$$

Since cellular membranes are relatively impermeable to electrolytes when compared to water, the amount of sodium in the intracellular fluid will remain constant.

$$\frac{d(TINA)}{dt} = 0 \quad (46)$$

The concentration of sodium in the extracellular compartment (PNa) and the intracellular compartment (INa) will then be given by

$$PNa = \frac{TENA}{E} \quad (47)$$

$$INa = \frac{TINA}{I} \quad (48)$$

where E is the extracellular fluid volume and I is the intracellular fluid volume.

Total body water balance A mass balance on total body water (W) gives

$$dW/dt = FLUMIN - UFL \quad (48)$$

where FLUMIN is the flow rate of water into the body. Assuming instantaneous osmotic equilibration between the intracellular (I) and extracellular (E) compartments

$$(TENA + TEC)/E = (TINA + TIC)/I \quad (50)$$

where TEC and TIC are constants which represent the other dissolved species within the extracellular and intracellular compartments, respectively. Instantaneous osmotic equilibrium between the extracellular and intracellular compartments will be assumed only when testing the kidney model. Since the mass transfer coefficient for the transfer of water across cellular membranes is known (see figure 1), the overall model of the body water compartments will not assume instantaneous equilibrium.

Since  $W = E + I$ , the size of the intracellular and extracellular compartments can be derived from equation (50).

$$E = W/[1 + (TINA + TIC)/(TENA + TEC)] \quad (51)$$

$$I = W/[1 + (TENA + TEC)/(TINA + TIC)] \quad (52)$$

### Testing the kidney model

To test the validity of the proposed kidney model, results predicted by the model will be compared to actual data involving injected or ingested fluids and subsequent urine flow rates. Under these conditions, water enters the body through the plasma compartment and leaves the body through the formation of urine. Intravenously injected fluids enter the plasma compartment immediately whereas ingested fluid must first be absorbed by the intestines. The rate constant for water absorption from the gastrointestinal tract has been estimated

to be  $3.33\text{hr}^{-1}$  (see figure 1). Amounts of water produced by cellular metabolism and excreted through sensible and insensible perspiration will be relatively small and consequently neglected for this case. Comparison of the model simulation to actual data following the ingestion of 1 liter of water is shown in figure 18. In figure 19, the model simulation is shown with actual data following the intravenous infusion of hypertonic saline.

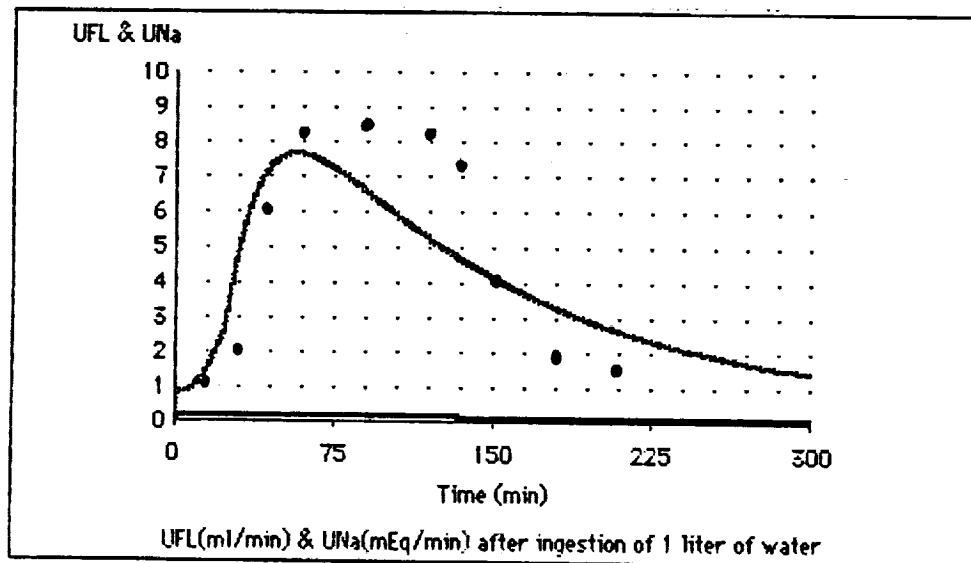


Figure 18: Results from the model simulation (solid line) and experimental data (solid circles) following ingestion of 1 liter of water. (actual data taken from Baldes & Smirk, 1934)

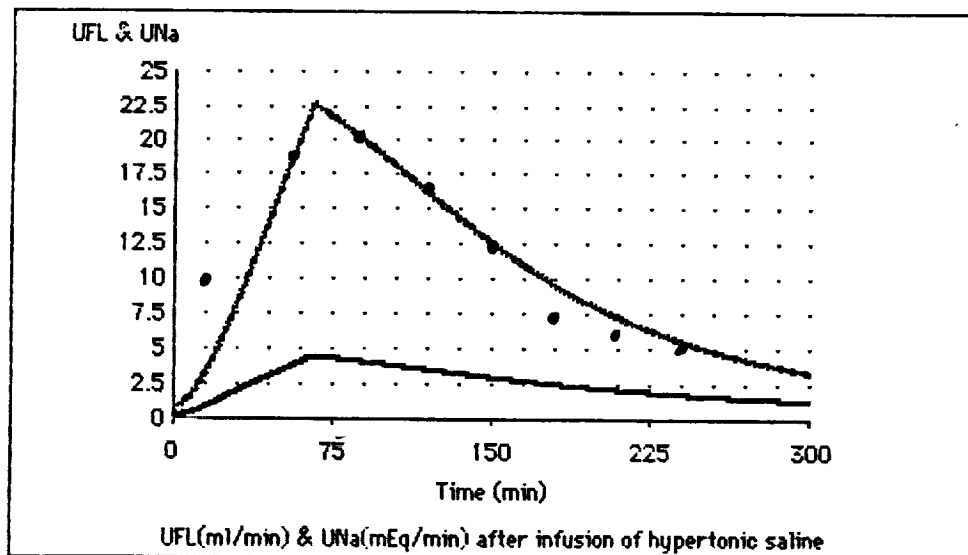


Figure 19: Results from the model simulation (solid line) and experimental data (solid circles) following infusion of 9.8 g/min of a 10% NaCl solution for 65 minutes. (actual data taken from Dean & McCance, 1949)

## Nomenclature

Symbol	Description	Typical value
A	concentration of angiotensin II in plasma (ng/l)	27.0
ADH	concentration of ADH in plasma (munits/l)	4.0
ADHS	net release rate of ADH (munits/min)	0.825
ADHSP	release rate of ADH due to plasma osmolality (munits/min)	0.84
ADHSV	release rate of ADH due to diminished fluid volume (munits/min)	0.81
ALD	concentration of aldosterone in the plasma (ng/l)	85.0
ALS	net rate of secretion of aldosterone (ng/min)	52.7
AP	arterial pressure (torr)	100.0
AS	rate of formation of angiotensin II (ng/min)	105.0
BV	blood volume (l)	5.0
CO	cardiac output (l/min)	5.0
DADH	clearance rate of ADH (l/min)	0.206
DWV	excess fluid in extracellular compartment (l)	0.0
E	extracellular fluid volume (l)	15.0
E <sub>N</sub>	normal extracellular fluid volume (l)	15.0
EBLH	fraction of water reabsorbed in the loop of Henle	0.33
EDTR	rate of reabsorption of water in the distal nephron segments (ml/min)	19.7
EFDT	rate of flow of water into the distal tubule (ml/min)	
EFLH	rate of flow of water into the loop of Henle (ml/min)	31.25
ELHR	rate of reabsorption of water in the loop of Henle (ml/min)	10.55
EPTR	rate of water reabsorption in the proximal tubule (ml/min)	93.75
FLUMIN	rate of ingestion of water (ml/min)	*
FNa	filtered load of sodium (mEq/min)	17.75
GFR	glomerular filtration rate (ml/min)	125.0
GTB	fraction of filtered load of sodium reabsorbed in the proximal tubule	0.75
Hct	hematocrit (unitless)	0.47 males 0.42 females
I	intracellular fluid volume (l)	25.0
INa	intracellular concentration of sodium (mEq/l)	10.0
K <sub>f</sub>	capillary filtration coefficient (ml/min·kg·torr)	0.061
MSP	mean systemic pressure (torr)	7.0
P <sub>c</sub>	capillary hydrostatic pressure (torr)	27.0
P <sub>i</sub>	interstitial hydrostatic pressure (torr)	1.0
PK	extracellular concentration of potassium (mEq/l)	5.0
PNa	extracellular concentration of sodium (mEq/l)	142.0
POS	plasma osmolality (mEq/l)	299.6
PV	plasma volume (l)	3.0
R	concentration of renin in plasma (GU/l)	0.06

RS	rate of release of renin (GU/min)	0.008
RVR	resistance to venous return (torr/l·min)	1.4
SDTR	rate of reabsorption of sodium from the distal nephron segments (mEq/min)	0.757
SFDT	rate of flow of sodium into the distal tubule (mEq/min)	0.89
SFLH	rate of flow of sodium into the loop of Henle (mEq/min)	4.44
SLHR	rate of reabsorption of sodium from the loop of Henle (mEq/min)	3.55
SODMIN	rate of ingestion of sodium (mEq/min)	*
SPTR	rate of reabsorption of sodium from the proximal tubule (mEq/min)	13.3
TEC	total extracellular osmotic components other than sodium (mEq)	2418.0
TENa	total extracellular sodium (mEq)	2130.0
TIC	total intracellular osmotic components other than sodium	7555.0
TINa	total intracellular sodium (mEq)	250.0
TPR	total peripheral resistance (torr/l·min)	20.0
UFL	urine flow rate (ml/min)	1.0
UNa	rate of excretion of sodium (mEq/min)	0.128
VR	venous return (l/min)	5.0
W	total body water (l)	40.0
$\pi_c$	capillary oncotic pressure (torr)	25.0
$\pi_i$	interstitial oncotic pressure (torr)	0.0

(\* subject dependent variable)



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# APPENDIX 3



Modifications to an interactive model  
of the human body during exercise:  
With special emphasis on thermoregulation

by

Megan Kay Scherb

A Creative Component Submitted to the  
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## NOMENCLATURE

AGE	Age of the athlete, years
GAIN1	Gain constant based on level of training
GAIN2	Gain constant based on level of dehydration
HT	Height of the athlete, cm
MKG	Mass of the athlete, kg
T <sub>s</sub>	Mean skin temperature
T <sub>head</sub>	Temperature of the head
T <sub>arm</sub>	Temperature of the arms
T <sub>hand</sub>	Temperature of the hands
T <sub>ft</sub>	Temperature of the feet
T <sub>leg</sub>	Temperature of the legs
T <sub>th</sub>	Temperature of the thighs
T <sub>tr</sub>	Temperature of the trunk
VO <sub>2max</sub>	Maximum oxygen uptake

## INTRODUCTION

Since 1988 an interactive computer model of the human body during exercise has been under development by a number of undergraduate students in the Department of Chemical Engineering at Iowa State University. The program, written under the direction of Dr. Richard C. Seagrave, uses physical characteristics of the user, environmental conditions and activity information to predict the onset of hypothermia, hyperthermia, dehydration, or exhaustion for various levels and durations of a specified exercise. The program, however, was severely limited in predicting the onset of dehydration due to the lack of sophistication with which the program predicted sweat rate and its relationship to sensible water loss, degree of acclimatization, and level of physical training. Additionally, it was not known whether sweat rate also depended on age and gender. For these reasons, the goal of this creative component was to modify the program in the above mentioned areas by applying known information and empirical relationships from literature. Furthermore, a secondary goal was to improve the consistency with which the program was written by modifying user input statements and improving the efficiency and logic of the program calculations.

### Principle Mechanisms of Heat Transfer During Exercise

The human body exchanges heat with the environment by four basic mechanisms; radiation, conduction, convection, and evaporation. These mechanisms are the same whether heat is imposed to the body metabolically, as in exercise, or environmentally. Radiative heat transfer occurs by the

transmission of electromagnetic heat waves between objects without the involvement of molecular contact. Heat transfer by radiation may result in either heat loss or gain depending on conditions in the environment. For example, when a person is cooler than the surroundings, he/she will absorb radiant heat energy. Conversely, when a person is warmer than the surroundings, he/she will lose heat to the environment.

Conductive heat transfer occurs when heat energy is transferred between objects by direct physical contact. Approximately three percent of a person's total heat loss at rest in a room temperature environment occurs via this mechanism (Brooks et al., 1987). Therefore, during exercise, heat loss by means of conduction is considered negligible. Conduction also occurs within the body itself as heat is conducted from the inner core to the skin or vice versa depending on the temperature gradient.

Convective heat transfer, a form of conduction of heat to a fluid, occurs via the circulation of air molecules adjacent to the skin. As air molecules are warmed, they become less dense, rise away from the body, and are displaced by cooler molecules. During exercise in air, heat loss due to convection is influenced by both the velocity of the athlete and the wind.

Finally, evaporative heat transfer occurs by way of the change of liquid water on the surface of the skin to gaseous water vapor in the environment. Evaporative heat transfer is the most important mechanism of heat transfer during exercise. In evaporation, heat is transferred from the body to water on the surface of the skin. When the water has gained sufficient energy, approximately 0.58 kilocalories per gram of water depending on the skin temperature, it vaporizes and heat is removed from the skin. It is important to note that unlike

radiation, conduction, and convection which occur because of temperature gradients, evaporation is driven by a gradient in the vapor pressure. During exercise, this fact is especially salient in an environment where the ambient temperature and relative humidity are high. In this situation, the body gains heat by convection and radiation, and evaporation becomes the only mechanism by which the body can lose heat. However, when the relative humidity is high, temperature regulation becomes more difficult because the vapor pressure of the air is close to that of moist skin. Therefore, the rate of evaporation is greatly reduced. Sweating in these environments results in sensible water loss that can lead to dehydration without a cooling effect to the skin (McArdle, 1986).

In addition to the four basic mechanisms of heat transfer, heat loss via respiration (a combined mechanism) must also be considered during exercise. Respiratory energy losses occur via the evaporation of water in the lungs and respiratory tract as well as by the convective cooling effect of breathing.

### **Physiological Control of Heat Transfer During Exercise**

There are two principle mechanisms by which the body can control the balance between heat production and heat loss during exercise. First, the body can change its surface temperature by altering blood flow to the skin. When blood vessels to the skin dilate (vasodilation), warm blood from the core of the body is brought to the surface where heat is lost via radiation and convection. Conversely, when these blood vessels constrict (vasoconstriction), heat is conserved in the inner core and less heat is lost to the surroundings. Second, the body can regulate the rate of sweating.



These physiological mechanisms are governed by the thermoregulatory center located in the hypothalamus. The hypothalamus functions as the body's thermostat by maintaining the body core temperature within a narrow range around its set-point of 37 degrees Celsius. When the core temperature increases above or decreases below this set-point, the hypothalamus initiates a response to increase or decrease heat production or facilitate heat loss.

The anterior hypothalamus reacts to increases in body heat, while the posterior hypothalamus is responsible for regulating reactions to a cold environment (Åstrand, 1986). Therefore, when the anterior hypothalamus senses an increase in core temperature above the set-point, it stimulates the sweat glands resulting in increased evaporative cooling. In addition, normal vasoconstriction is inhibited and blood flow to the skin is promoted. Conversely, when the posterior hypothalamus senses a decrease in core temperature below the set-point, the vasomotor center causes the peripheral blood vessels to constrict and, if the core temperature drops significantly, shivering commences.

## LITERATURE REVIEW

Numerous reviews on the subject of exercise thermoregulation have been written in the past two and a half decades. For additional information on this subject, the reader is referred to two of the more recent reviews, Gisolfi et al. (1984) and Buskirk (1977).

Before specifically addressing the areas of interest of this work, it is necessary to provide background information regarding the relationships of physiological variables such as skin and core temperature to effector responses.

Since body tissue temperatures differ based on local rates of heat production and heat exchange as well as heat transfer between locations in the body, definitions are necessary to specify these variations. This paper will only consider the differences between core and skin temperatures.

Deep-body, or core temperature, is usually measured at one of three locations; rectum, esophagus or the tympanic membrane. These estimates of core temperature are not wholly equivalent to each other, but have been shown to vary in parallel and are thus effective measures of relative changes (Åstrand, 1986).

Skin temperature can be determined by assigning weights to specific skin temperature measurements at various locations on the body in proportion to the fraction of the body's total surface area represented by that location. The most commonly used formula which was developed by Hardy and Dubois follows (Åstrand, 1986):

$$T_s = 0.07 T_{\text{head}} + 0.14 T_{\text{arm}} + 0.05 T_{\text{hand}} + 0.07 T_{\text{ft}} + 0.13 T_{\text{leg}} + 0.19 T_{\text{th}} + 0.35 T_{\text{tr}}$$

It is generally accepted that skin temperature is dependent on the environmental temperature surrounding the skin and is relatively independent of exercise load. Conversely, the core temperature is independent of the ambient temperature and is largely dependent on the relative exercise load, as expressed as a percentage of maximum oxygen uptake,  $\text{VO}_{2\text{ max}}$  (Åstrand, 1986). For example, if two people perform the same absolute work load but have different

maximum oxygen uptakes, the person with the lower  $\text{VO}_2 \text{ max}$  will experience a greater rise in core temperature. However, if the same two people exercise at the same percentage  $\text{VO}_2 \text{ max}$ , their core temperatures should increase by approximately the same amount.

In contrast, sweat rate is more closely related to the absolute work load than to relative work load (Buskirk, 1977). Furthermore, body core temperature can be as much as ten times more influential on sweat rate than skin temperature (Wyndham, 1965). Wyss et al. (1974) supported this finding by concluding that sweat rate was virtually independent of steady state skin temperature and that body core temperature was the dominant factor in skin blood flow, heart rate and sweat rate determination. Additionally, Davis et al. (1976) concluded that skin temperature was independent of evaporative sweat loss and relative exercise load.

### **Effects of Heat Acclimatization and Physical Training**

Adaptations to sweating are typically caused by both an exercise and a heat effect (Nadel et al., 1974). However, it has been shown that these adaptations occur via two different mechanisms. Physical training results in enhanced sweating at a given level of central drive. The increased metabolic rate during training increases thermoregulatory demand and induces an increased peripheral sensitivity of the sweat glands (Nadel et al., 1974). In other words, physical training increases the slope of the sweat rate versus core temperature relationship. Nadel et al. (1974) noted an increase of 67 percent in this slope as a result of ten consecutive days of one hour exercise at a relative exercise intensity of 70 to 80 percent  $\text{VO}_{2\text{max}}$ .

In contrast to physical training, heat acclimatization lowers the threshold core temperature at which sweating starts, increases sweating capacity, decreases skin temperature, and reduces the heart rate (Nadel et al., 1974; Fortney and Senay, 1979; Frye and Kamon, 1981; Horstman and Christensen, 1982). Nadel et al. (1974) noted a 0.3 degree Celsius decrease in the threshold core temperature, while Brooks et al. (1987) noted a three fold increase in sweating capacity from 1.5 to 4 kilograms per hour as a result of heat acclimatization.

According to Bass (1963), the acclimatization process begins on the first day of exposure and is well developed in 4 - 7 days. It can be induced by short intermittent periods of work or exercise in the heat, and is retained during periods of no exposure for about two weeks. Additionally, persons in good physical condition tend to acclimatize more rapidly than unfit subjects. However, physical training cannot replace heat acclimatization (Strydom et al., 1966; Gisolfi and Cohen, 1979). Training results in partial acclimatization that may improve heat tolerance by up to 50 percent (Gisolfi and Cohen, 1979), but training alone cannot substitute for exercise in the heat.

Figure 1 of Appendix A illustrates schematically the effects on sweat rate of both heat acclimatization and physical training discussed above.

### **Effect of Dehydration**

As noted previously, athletes who exercise for prolonged periods can lose up to four liters of body fluids in the form of sweat and can experience a total weight loss of seven to eight percent of body weight during an endurance event such as a marathon (Lamb, 1984). Since the body contains only 40 liters of fluid, of which 5 liters are blood, loss of a large portion of this fluid results in a decrease

in blood volume, cardiac output, and blood pressure. A loss of two to three liters of body fluids during exercise causes a reduction in sweating which results in an increase in core temperature (Nadel, 1979). The data of Greenleaf and Castle (1971) show that at a level of dehydration equivalent to loss of fluid equal to about five percent body weight, core temperature increases significantly due to inadequate sweating. Nadel (1979) further postulates that dehydration causes a reduction in the sensitivity of the sweat rate. In other words, dehydration decreases the slope of the sweat rate versus core temperature relationship. Please refer to Figure 2 in Appendix A for a schematic illustration of this effect.

### Effects of Age and Gender

Although the experimental data are limited, the evidence in literature suggests that there are few differences in the thermoregulatory responses which can be ascribed to age and gender (Davies, 1979). Studies by Drinkwater et al. (1982) show that the functional capacity of the sweating mechanism in healthy older women does not decrease with age. Additionally, no differences were reported between the sexes with respect to sweat rate or efficiency in dry heat, but women maintained a higher sweating efficiency in humid heat (Frye and Kamon, 1983). This increased efficiency allows women to conserve body water while maintaining a similar core temperature to that of men. In other words, for the same degree of evaporative cooling, women secrete less wasteful sweat. When men and women of similar fitness levels are compared, the previously reported gender differences with respect to heat exposure disappear (Avellini et al., 1980). Furthermore, Horstman and Christensen (1982) concluded that active

men and women compared at the same level of relative exercise intensity performed exercise equally well in dry heat.

## **PROGRAM MODIFICATIONS**

As many individuals had modified various parts of the program over the past four years, the program contained inconsistencies. Therefore, to improve the program two types of modifications were made; organizational changes and functional changes. Organizational changes involve modifications that changed the order in which the program performed specific operations. Functional changes are modifications that improved specific functions of the program, i.e. the consistency of wording in the user input statements, or changes to specific calculations.

In addition to the organizational and functional changes, specific modifications were made to the program as a result of information found in the literature. Modifications were made to account for the following effects; physical training, acclimatization to heat, and dehydration. Additionally, a modification was made to correct the program for its premature prediction of the onset of dehydration. Please refer to the program listing in Appendix C for an updated version of the program.

### **Organizational Changes**

Modifications which improve the flow and efficiency of the program are described below. Please refer to the flow diagram in Figure 3 of Appendix A for more detailed information regarding the general organization of the program.

- (1) The main program was divided into four sections: (a) user input, (b) calculation of constants and initial values, (c) calculation of material and energy balances, (d) calls for subroutines to calculate fuel usage, print summary information, and plot data.
- (2) The section which prints summary information was rewritten as a subroutine (PRINTAB).
- (3) The order of the user input statement was improved. The program now asks the user to input information in the following order; personal physical characteristics, environmental conditions and activity information.
- (4) All format statements were moved to the end of the program or subroutine to which they apply.

### Functional Changes

In order to improve the consistency of the program and the manner in which certain calculations are performed, the following modifications were made:

- (1) The number of variables and constants defined within the program was increased.
- (2) The language of the variable and constant definitions was improved to maintain consistent use of language throughout the list. Units of the variable or constant were also included in the definition.
- (3) Additional tests were added in the user input section to ensure valid information is entered.
- (4) Screen stops were added for all output printed to the screen.
- (5) The consistency of the language in the user input section was improved.
- (6) All FORTRAN 'print' statements were changed to 'write' statements to facilitate future modifications to input/output formats.

- (7) A question regarding the user's gender was added to the input section.
- (8) A subroutine PLOTDATA was added to plot program results versus time. These results include: core temperature, heat loss, body weight, and skin temperature.
- (9) Revised expressions were added to calculate basal metabolic rate (Olson, 1992). The expressions follow:

Female:  $\text{BASAL (kcal/day)} = 655.1 + 9.563 \text{ MKG} + 1.850 \text{ HT} - 4.676 \text{ AGE}$

Male:  $\text{BASAL (kcal/day)} = 66.5 + 13.75 \text{ MKG} + 5.003 \text{ HT} - 6.775 \text{ AGE}$

### Correction for Premature Prediction of Dehydration

Several simulations of the program at various levels and durations of exercise indicated that the program prematurely predicted the onset of dehydration. This occurred because the sweat rate equations estimate a high amount of sensible water loss as run-off. It is postulated by Seagrave that high quantities of run-off are estimated because Nielsen's (1969) sweat rate measurements were taken after steady state temperatures had been achieved. However, the program uses these sweat rate estimations in an unsteady state capacity. According to Kerslake (1963), loss of sweat by dripping does not begin until the sweat rate has reached one-third of the maximum evaporative capacity. Therefore, to improve the program, it is necessary to determine the point at which sweat run-off commences.

The program was modified by adding a statement to calculate one-third maximum evaporative capacity, the point at which sweating begins. If the sweat rate has not reached this point, the program uses the rate of evaporative mass transfer as an estimation of the water loss. However, if the sweat rate has



reached one-third maximum evaporative capacity, the program uses the water loss calculated by the WATERLOSS subroutine.

### **Effect of Heat Acclimatization**

Before any modifications could be made to the program, the existing sweat rate equations in the WATERLOSS subroutine had to be modified. These equations had been extrapolated by Woodard from data given in Nielson (1969). These relationships expressed sweat rate as a function of skin temperature at given metabolic rates and skin temperatures. These relationships were modified to express sweat rate as function of body core temperature, rather than skin temperature. To make this modification, core temperature, skin temperature and sweat rate data were generated using the program. Subsequently, linear regressions were performed on the data to generate equations which expressed sweat rate as a function of body core temperature for given skin temperatures and metabolic rates. Please see Table 1 in Appendix B for the revised sweat rate equations.

To account for heat acclimatization, two modifications were made. First, if the athlete is both acclimatized to heat and physically trained, the maximum sweat rate (MAXSR) is set to 4.0 kilograms per hour and the set-point of the body core temperature is lowered by 0.3 degrees Celsius to 36.7 degrees. However, if the athlete is not acclimated to heat, the maximum sweat rate is set to 1.5 kilograms per hour and the body core temperature is set to the standard set-point of 37 degrees Celsius.

### Effect of Physical Training

To modify the program for the effect of physical training on sweat rate, statements were added to section 2 of the main program to change the slope of the sweat rate equations that appear in subroutine WATERLOSS. If an athlete is trained, GAIN1 is set to 1.65, or the slope of the sweat rate equation is increased by 65%. However, if the athlete is not trained, there is no change to the slope of the sweat rate equation and GAIN1 is set equal to 1.0.

### Effect of Dehydration

To account for the effect of dehydration, statements were added to adjust the slope of the sweat rate equations in the WATERLOSS subroutine as dehydration progresses. The gain constants were chosen somewhat arbitrarily due to the lack of specific numerical information provided in the literature. However, statements were added in section 3 of the main program to adjust the slope of the sweat rate equations in the following manner; when the body is less than one percent dehydrated, no change is made to the slope of the sweat rate equation or GAIN2 is set to 1.0. When total dehydration is between one and two percent, the slope of the sweat rate equation is decreased by five percent or GAIN2 is set to 0.95. For increasing percentages of dehydration, the slope is decreased in ten percent increments to a maximum level of dehydration of five percent of the total body weight. At this level of dehydration, the slope of the sweat rate equation has been decreased a total of 35 percent.

## RECOMMENDATIONS FOR FUTURE WORK

In order to improve the program the following recommendations are provided as areas of future work:

- (1) Modify the program to account for partial acclimatization to heat.
- (2) Modify the program to account for the fact that women are less wasteful sweaters.
- (3) Add sweat rate equations for metabolic rates greater than 1700 kilocalories per hour.
- (4) Further quantify the effect of dehydration on sweat rate.
- (5) Determine the effect of cold acclimatization on exercise thermoregulation.
- (6) Quantify the effect of transverse wind velocity on the total velocity.
- (7) Quantify maximum glucose usage for all exercises included in the program

## LITERATURE CITED

- Åstrand, P. O., K. Rodahl, 1986. Temperature Regulation. Pages 585 - 635, *Textbook of Work Physiology*. McGraw Hill, New York.
- Avellini, B. A., E. Kamon, and J. T. Krajewski, 1980. Physiological responses of physically fit men and women to acclimatization to heat, *J. Appl. Physiol.*, 49(2):254.
- Bass, E. E., 1963. Thermoregulatory and circulatory adjustments during acclimatization to heat in man. Pages 299 - 305 in J. D. Hardy (ed.), *Temperature: Its Measurement and Control in Science and Industry*, vol. 3, part 3, Reinhold Book Corporation, New York.
- Buskirk, E. R., 1977. Temperature regulation with exercise, in R. Terjung (ed.), *Exercise Sport Sci. Rev.*, 5:45.
- Brooks, G. A., T. D. Fahey, 1987. Temperature and exercise. Pages 264 - 285, *Fundamentals of Human Performance*, Macmillian Pub. Co., New York.
- Davies, C. T. M., 1979. Thermoregulation during exercise in relation to sex and age, *Eur. J. Appl. Physiol.*, 42:71.
- Davies, C. T. M., J. R. Brotherhood, and E. Zeidifard, 1976. Temperature regulation during severe exercise with some observation on effects of skin wetting, *J. Appl. Physiol.*, 41(5):772.
- Drinkwater, B. L., J. F. Bedi, A. B. Louks, S. Rouche, and S. M. Horvath, 1982. Sweating sensitivity and capacity of women in relation to age, *J. Appl. Physiol.*, 53(3):671.
- Fortney, S. M. and L. C. Senay, 1979. Effect of training and heat acclimation on exercise responses of sedentary females, *J. Appl. Physiol.*, 47(5):978.
- Frye, A. J. and E. Kamon, 1983. Sweating efficiency in acclimated men and women exercising in humid and dry heat, *J. Appl. Physiol.*, 54(4):972.
- Frye, A. J. and E. Kamon, 1981. Responses to dry heat of men and women with similar aerobic capacities, *J. Appl. Physiol.*, 50:65.

- Gisolfi, C. V. and J. S. Cohen, 1979. Relationships among training, heat acclimation, and heat tolerance in men and women: The controversy revisited, *Med. Sci. Sports*, 11:56.
- Gisolfi, C. V. and C. B. Wegner, 1984. Temperature regulation during exercise: Old concepts, new ideas, in R. Terjung (ed.), *Exercise Sport Sci. Rev.*, 12:339.
- Greenleaf, J. E. and B. L. Castle, 1971. Exercise temperature regulation in man during hypohydration and hyperhydration, *J. Appl. Physiol.*, 30(6):847.
- Horstman, D. H. and E. Christensen, 1982. Acclimatization to dry heat: Active men vs. active women, *J. Appl. Physiol.*, 52(4):825.
- Kerslake, D. Mck., 1963. Errors arising from the use of mean heat exchange coefficients in calculation of the heat exchanges of a cylindrical body in a transverse wind. Pages 183 - 190 in J. D. Hardy (ed.), *Temperature: Its Measurement and Control in Science and Industry*, vol. 3, part 3, Reinhold Book Corporation, New York.
- Lamb, D. R., 1984. Temperature regulation during exercise. Pages 221 - 238, *Physiology of Exercise*, Macmillian Pub. Co., New York.
- McArdle, W.D., F. I. Katch, V. L. Katch, Exercise and Thermal Stress, 1986. Pages 441 - 466, *Exercise Physiology: Energy Nutrition and Human Performance*, Lea and Febiger, Philadelphia, PA.
- Nadel, E. R., 1979. Control of sweating rate while exercising in the heat, *Med. Sci. Sports*, 11(1):31.
- Nadel, E. R., K. B. Pandolf, M. F. Roberts, and J. A. Stolwijk, 1974. Mechanisms of thermal acclimation to exercise and heat, *J. Appl. Physiol.*, 37(4):545.
- Nielsen, B., 1969. Thermoregulation in rest and exercise, *Acta Physiol. Scand.* (Suppl. 323).
- Olson, C. E., 1992. Integration of human material and energy balance in life support system descriptions, AeroE 499 Project, Iowa State University, Ames, IA.
- Strydom, N. B., C. H. Wyndham, C. G. Williams, J. F. Morrison, G. A. G. Bredell, A. J. S. Benade, and M. von Rahden, 1966. Acclimatization to humid heat and the role of physical conditioning, *J. Appl. Physiol.*, 21:636.

- Woodard, L. K., 1988. Model of the human body during exercise, ChE 490 Project, Iowa State University, Ames, IA.
- Wyndham, C. H., 1965. Role of skin and core temperature in man's temperature regulation, *J. Appl. Physiol.*, 20(1):31.
- Wyss, C. R., G. L. Brengelmann, J. M. Johnson, L. B. Rowell, and M. Niederberger, 1974. Control of skin blood flow sweating, and heart rate: Role of skin vs. core temperature, *J. Appl. Physiol.*, 36(6):726.

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**APPENDIX A:**



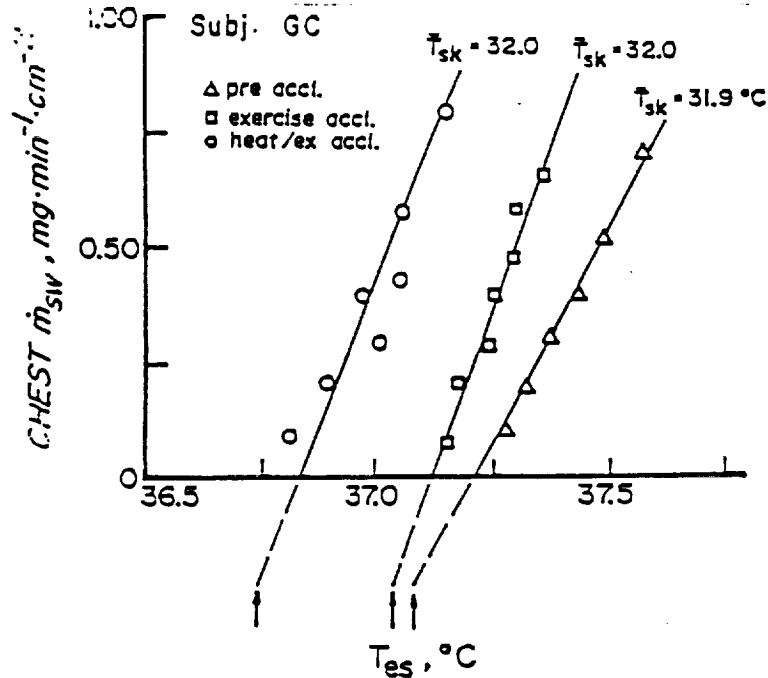


Figure 1: Chest sweating rate as a function of esophageal temperature prior to acclimatization, following 10 days of physical training and following 10 day of heat acclimatization. (Taken from Nadel, 1974)

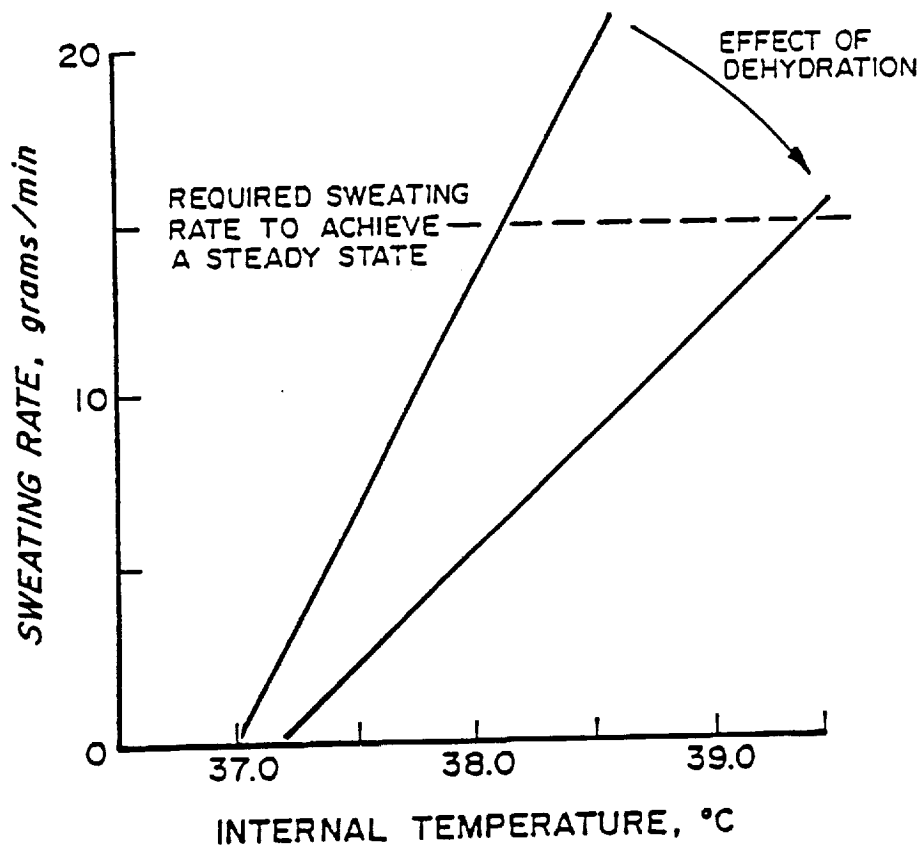
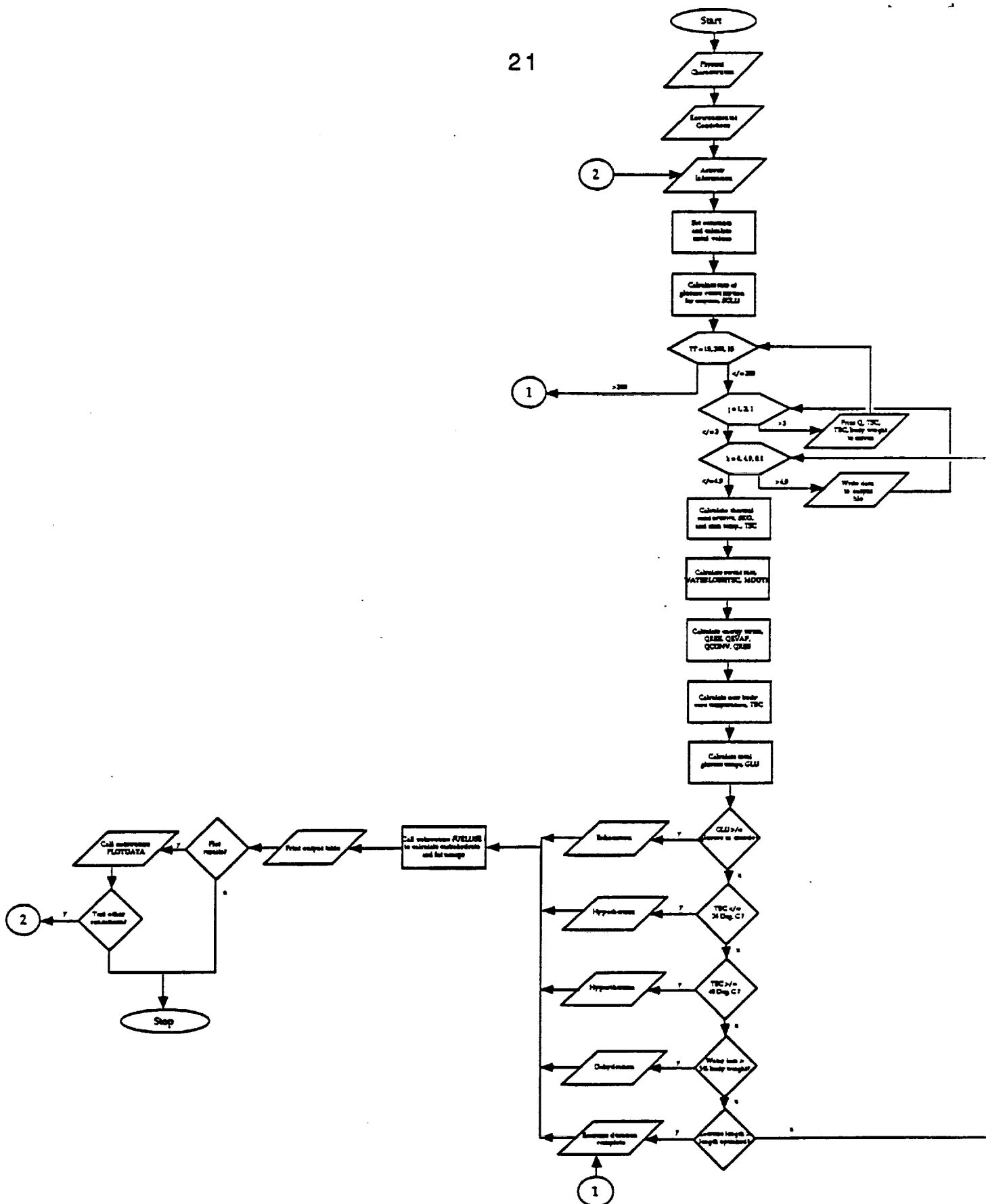


Figure 2: A schematic representation of one possible effect of dehydration on the sweating rate as a function of internal temperature. (Taken from Nadel, 1979)



**APPENDIX B:**

**Table 1: Revised Sweat Rate Equations**

Metabolic Rate (kcal/hour)	TSC Constraint(s) (Deg. C)	Regression Equation:
Less than 300	None	$DSWEAT = 0.046122 \text{ TBC} - 1.16399$
301 - 500	$\leq 33.0$	$DSWEAT = 0.063091 \text{ TBC} - 1.53415$
	$> 33.0$	$DSWEAT = 0.295611 \text{ TBC} - 9.53531$
501 - 700	$\leq 33.4$	$DSWEAT = 0.091916 \text{ TBC} - 2.21063$
	$> 33.4$	$DSWEAT = 0.512109 \text{ TBC} - 16.9846$
701 - 900	$\leq 32.0$	$DSWEAT = 0.223172 \text{ TBC} - 6.03852$
	$> 32.0$	$DSWEAT = 0.390976 \text{ TBC} - 11.8576$
901 - 1100	None	$DSWEAT = 0.256577 \text{ TBC} - 5.75055$
1101 - 1300	$\leq 29.0$	$DSWEAT = 0.439115 \text{ TBC} - 12.3871$
	$> 29.0$	$DSWEAT = 0.314289 \text{ TBC} - 8.09200$
1301 - 1500	$\leq 28.6$	$DSWEAT = 0.699080 \text{ TBC} - 21.2381$
	$> 28.6$	$DSWEAT = 0.227225 \text{ TBC} - 4.99327$
1501 - 1700	None	$DSWEAT = 0.053090 \text{ TBC} + 1.639657$

**APPENDIX C: PROGRAM LISTING**

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MODEL OF THE HUMAN BODY AND EXERCISE

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REAL Y,N,WTLBS,MKG,TIC,WMPH,WMETPS,BASAL,GAIN1,GAIN2
REAL RHUM,MDOT,VMPH,VMETPS,VELTOT,TBC,HV,PA,YA,AIRMOL
REAL VAIRL,VOMAX,MILE,IPVO,PVO,SGLU,TSC,DSWEAT,PS,SWEAT,DTB
REAL TSWEAT,DGLU,GLU,QRES,QEVAP,QCONV,QRAD,QTOT,CB,AC,HC,CA
REAL KG,AV,AR,HR,TIF,VOL,LRA,CLO,K,YARRAY(40),WATERLOSS
REAL CHFRAC,LFRAC,CHEQ,LIPEQ,TOTCAL,CHCAL,LIPCAL,CALEQ
REAL LIPUSED,CHUSED,BCM,BCMB,QUAD,HAM,BICEP,TRICEP,CALF
REAL HTVAP,EMAX,DRIP,MAXSR,TS

```

```

CHARACTER ANS*4,C*1,WW*3,GENDER*1,ICASE*1
CHARACTER NAME*50,EXDESC*50,CLOTHES*50,BOXANS*15,FRAME*15

```

```

INTEGER TT,NUMDAT,ICLO,CHOICE,I,XARRAY(40)
INTEGER AGE,FT,IN,MIN,SEC,TTMAX,ACTLEV,ACCLEV

```

```

COMMON NAME,FT,IN,WTLBS,AGE,CLOTHES,MIN,SEC,ACTLEV,EXDESC
COMMON MDOT,VOL,VMPH,TIF,RHUM,WMPH,TS,CBW,CBT,FTSC,TOTCAL
COMMON CHCAL,LIPCAL,CHUSED,LIPUSED,TIME

```

```

write(*,2) 'This program is designed to inform well trained'
write(*,*) 'and novice athletes how long they may exercise at'
write(*,*) 'a certain level before one of the following'
write(*,*) 'conditons occur:'
write(*,1)
write(*,3) 'a) hyperthermia: estimated core temperature'
write(*,3) ' surpasses 40 Deg. C (104 Deg. F)'
write(*,3) 'b) dehydration: loss of body water exceeds 5%'
write(*,3) ' of body weight'
write(*,3) 'c) estimated muscle glycogen supply exceeded'
write(*,3) 'd) hypothermia: estimated core temperature'
write(*,3) ' drops below 34 Deg. C (92 Deg. F)'
write(*,1)

```

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PROGRAM VARIABLES/CONSTANTS

<u>VARIABLE/CONSTANT</u>	<u>DESCRIPTION</u>
AC	Body area available for convection (94% total body area, m^2)
ACCLEV	Level of acclimatization of user (heat, cold, unacclimatized)
ACTLEV	Activity level of user (trained/untrained)
AGE	Age of the athlete (years)

* AIRMOL	Air intake conversion (mol/hr)	*
* ANS	Answer to question (yes/no)	*
* AR	Body area available for radiation (78% total body area, m <sup>2</sup> )	*
* AV	Body area available for evaporation (15% total body area, m <sup>2</sup> )	*
* BASAL	Basal metabolic rate (kcal/min)	*
* BCM	Volume of body (m <sup>3</sup> )	*
* BCMB	Volume of body taking into account body build (m <sup>3</sup> )	*
* HAM	Glycogen content in hamstrings (mmol)	*
* BICEP	Glycogen content in bicep (mmol)	*
* BSA	Surface area of body as a function of athlete height and mass (m <sup>2</sup> )	*
* CA	Heat capacity of air (kcal/gmole*Deg. C)	*
* CALF	Glycogen content in calf (mmol)	*
* CB	Heat capacity of the body (kcal/kg*Deg. C)	*
* CBT	Current body temperature (Deg. F)	*
* CBW	Current body weight (lbs)	*
* CLO	Clothing correction factor	*
* CU	Carbohydrates used by muscle (grams)	*
* DGLU	Glucose used initially (grams)	*
* DRIP	One-third maximum evaporative capacity (kcal/min)	*
* DSWEAT	Sweat rate as a function of skin temperature (kg/hr)	*
* DTB	Body temperature change (Deg. C/6 sec)	*
* EMAX	Maximum evaporative capacity (kcal/6 sec)	*
* EXDESC	Type of exercise	*
* FRAME	Body frame size of user (small/medium/large)	*
* FT	Height of user (inches)	*
* FTSC	Skin temperature (Deg. F)	*
* GAIN1	Gain constant used in modifying sweat rate based on level of training	*
* GAIN2	Gain constant used in modifying sweat rate based on level of dehydration	*
* GENDER	Gender of the user (male/female)	*
* GLU	Glucose used (grams/6 sec)	*
* HC	Convective heat transfer coef. (kcal/(m <sup>2</sup> *hr*C))	*
* HR	Radiative heat transfer coef. (kcal/(m <sup>2</sup> *hr*C))	*
* HD	Difference between heat generated and heat lost	*
* HT	Height of user (cm)	*
* HV	Heat transfer coefficient for vaporization (kcal/(m <sup>2</sup> *hr*mmHg))	*
* HVAP	Heat of vaporization of water @ 37 Deg. C (kcal/mol)	*
* ICLO	Input indication of user clothing factor	*
* IOPTION	Program calculation option	*
* KG	Mass transfer coefficient for evaporation of water (kg/(hr*mmHg*m <sup>2</sup> ))	*
* MAXSR	Maximum sweat rate depending on level of acclimatization (kg/hr)	*
* MDOT	Metabolic energy rate (kcal/hr)	*
* MILE	Time of mile (min)	*
* MIN	Time of mile (min)	*

* MKG	Athlete's mass (kg)	*
* N	No, answer to question	*
* NAME	Name of program user	*
* NUMDAT	Counter used to determine number of data points sent to output file	*
* PA	Vapor pressure of water at ambient temperature using the Antoine equation (mmHg)	*
* PS	Vapor pressure of water at skin temperature using the Antoine equation (mmHg)	*
* PVO	Percent maximum oxygen capacity required for a certain level of exercise (%)	*
* QCONV	Heat transfer by convection (kcal/min)	*
* QEVAP	Heat transfer by evaporation (kcal/min)	*
* QRAD	Heat transfer by radiation (kcal/min)	*
* QRES	Energy lost in respiration (kcal/min)	*
* QTOT	Total heat transfer (kcal/min)	*
* QUAD	Glycogen content in quad (mmol)	*
* RHUM	Relative humidity	*
* SEC	Time of mile (s)	*
* SGLU	Rate of glucose consumption at a certain level of exercise (mmol/kg*min)	*
* SKO	Thermal conductivity of skin at given body core temperature (kcal/(m*min*Deg. C))	*
* SWEAT	DSWEAT conversion (kg/6 sec)	*
* TBC	Body core temperature (Deg. C)	*
* TIC	Initial ambient temperature (Deg. C)	*
* TIF	Initial ambient temperature (Deg. F)	*
* TRICEP	Glycogen content in tricep (mmol)	*
* TSC	Relation for body skin temperature	*
* TSWEAT	Added water loss (kg)	*
* TT	Time counter (min)	*
* VAIRL	Rate of air intake for a particular exercise wrt MDOT (l/min)	*
* VMETPS	Velocity created by the athlete (m/s)	*
* VMPH	Velocity created by the athlete (miles/hr)	*
* VELTOT	Total net velocity of the wind (created by the athlete and the environmental conditions)	*
* VOL	Required oxygen consumption for a particular exercise	*
* VOMAX	Variable for maximum oxygen capacity of a particular athlete	*
* WMETPS	Wind velocity (m/s)	*
* WMPH	Wind velocity (miles/hr)	*
* WTLBS	Athlete's weight (lbs)	*
* WW	Response to wind direction question	*
* Y	Yes, answer to question	*
* YA	Mole fraction of water in air	*
* Z	Rate of mass transfer by evaporation (kg/hr)	*
* *****		*



```
*****
*
*   SECTION 1: This section asks the user to input their physical
*   characteristics, environmental conditions, and the desired type of
*   exercise.
*
*****
```

C     — Enter physical characteristics

```

write(*,2) 'Please enter your name (50 character max): >'
read(*,4) NAME

write(*,2) 'Gender is used in calculating basal metabolic rate.'
write(*,1)
9  write(*,*) 'If you are a female, please enter F;'
   write(*,*) 'if you are a male, please enter M: >'
   read (*,4) GENDER

   if ((GENDER .NE. 'F') .AND. (GENDER .NE. 'M')
+    .AND. (GENDER .NE. 'f') .AND. (GENDER .NE. 'm')) then
       write(*,5)
       GOTO 9
   end if

10 write(*,2) 'This program is designed for athletes between'
   write(*,*) 'the ages of 18 and 75.'
   write(*,1)
   write(*,*) 'Please enter your age in years: >'
   read(*,*) AGE

   if ((AGE .LT. 18) .OR. (AGE .GT. 75)) then
       write(*,5)
       GOTO 10
   end if

11 write(*,2) 'Please enter your height (feet,inches): >'
   read(*,*) FT,IN

   if ((FT .LT. 0) .OR. (IN .LT. 0) .OR. (IN .GT. 12)
+    .OR. FT .GT. 7) then
       write(*,5)
       GOTO 11
   end if

12 write(*,2) 'Please enter your body weight (60 - 300 lbs): >'
   read(*,*) WTLBS

   if ((WTLBS .LT. 60) .OR. (WTLBS .GT. 300)) then
       write(*,5)

```

```

      GOTO 12
    end if

13    write(*,2) 'Please enter your approximate muscular build: >'
      write(*,*) '(small, medium, large)'
      read(*,4) FRAME

      if ((FRAME .NE. 'small') .AND. (FRAME .NE. 'large')
+      .AND. (FRAME .NE. 'medium')) then
        write(*,5)
        GOTO 13
      end if

14    write(*,2) 'Enter the number which best corresponds to your'
      write(*,*) 'clothing (in addition to your shoes): >'
      write(*,1)
      write(*,*) 'Shorts only, enter 1.'
      write(*,*) 'Shorts and short-sleeve shirt or singlet, enter 2.'
      write(*,*) 'Shorts and long-sleeve shirt, enter 3.'
      write(*,*) 'Legs covered and long-sleeve shirt, enter 4.'
      write(*,*) 'Legs, arms, hands, and head all covered, enter 5.'
      read(*,*) ICLO

      if (ICLO .NE. 1 .AND. ICLO .NE. 2 .AND. ICLO .NE. 3
+      .AND. ICLO .NE. 4 .AND. ICLO .NE. 5) then
        write(*,5)
        GOTO 14
      end if

C    — Environmental conditions

15    write(*,2) 'Please enter the air temperature (-40 to 120 Deg. F): >'
      read(*,*) TIF

      if ((TIF .LT. -40.0) .OR. (TIF .GT. 120)) then
        write(*,5)
        GOTO 15
      end if

16    write(*,2) 'Please enter wind velocity (0 - 50 miles/hr): >'
      read(*,*) WMPH

      if ((WMPH .GT. 50.0) .OR. (WMPH .LT. 0.0)) then
        write(*,5)
        GOTO 16
      end if

      if (WMPH .EQ. 0.0) then
        WMPH = WMPH + 1.0          ! Add 1 mph to account for free convection
        GOTO 17
      end if

```

```

25  write(*,1) 'On the average, is the wind opposing you (A) or
    write(*,*) 'following you (F), or neither (N)?'
    write(*,*) 'Please enter either A, F, or N: >'
    read(*,4) WW

    if ((WW .NE. 'A') .AND. (WW .NE. 'a') .AND.
+   (WW .NE. 'F') .AND. (WW .NE. 'f') .AND. (WW .NE. 'N') .AND. (WW .NE. 'n')) then
        write(*,5)
        GOTO 25
    end if

17  write(*,2) 'Please enter the relative humidity as a decimal: >'
    read(*,*) RHUM

    if ((RHUM .LT. 0.0) .OR. (RHUM .GT. 1.0)) then
        write(*,5)
        GOTO 17
    end if

C   — Enter activity information (duration,level,type)

18  write(*,2) 'Would you like the program to:'
    write(*,3) '(1) recommend a duration of exercise?'
    write(*,3) '(2) allow you to choose a duration of exercise?'
    write(*,1)
    write(*,*) 'Please enter 1 or 2: >'
    read(*,*) IOPTION

    if (IOPTION .NE. 1 .AND. IOPTION .NE. 2) then
        write(*,5)
        GOTO 18
    end if

    if (IOPTION .EQ. 1) then
        TTMAX = 300
    else
19  write(*,2) 'Please enter the duration of exercise (1 - 300 min): >'
        read(*,*) TTMAX
        if ((TTMAX .LE. 0) .OR. (TTMAX .GT. 300)) then
            write(*,5)
            GOTO 19
        end if
    end if

    if (TT .GT. 15) then
        GOTO 41
    end if

! Bypass activity information that
! does not change during subsequent
! tests of exercise conditions.

C   — The user's time for the mile run provides information about
C   maximal oxygen capacity and therefore maximal level of exercise

```

```

20  write(*,2) 'Do you know your best recent time for the mile?'
    write(*,*) 'If YES, please enter Y; if NO, please enter N: >'
    read(*,4) ANS

    if ((ANS .NE. 'Y') .AND. (ANS .NE. 'N') .AND. (ANS .NE. 'y')
+   .AND. (ANS .NE. 'n')) then
        write(*,5)
        GOTO 20
    end if

    if ((ANS .EQ. 'Y') .OR. (ANS .EQ. 'y')) then
21  write(*,2) 'Please enter your time for the mile (min,sec): >'
        read(*,*) MIN,SEC
        if ((MIN .LT. 4) .OR. (MIN .GT. 20) .OR. (SEC .GT. 60) .OR. (SEC .LT. 0)) then
            write(*,5)
            GOTO 21
        end if
    else
        MIN = 0
        SEC = 0
    end if

30  write(*,2) 'If best time for the mile is unknown, then maximum'
    write(*,*) 'oxygen capacity is based on age and activity level.'

39  write(*,2) 'Please select your normal level of activity:'
    write(*,3) '1) Active (well trained in distance sports)'
    write(*,3) '2) Inactive (no continuous training)'
    write(*,1)
    write(*,*) 'Please enter 1 or 2: >'
    read(*,*) ACTLEV

    if ((ACTLEV .NE. 1) .AND. (ACTLEV .NE. 2)) then
        write(*,5)
        GOTO 39
    end if

40  write(*,2) 'Please select level of acclimatization:'
    write(*,3) '1) Not acclimated to heat or cold'
    write(*,3) '2) Heat acclimated:'
    write(*,3) ' 7-10 days training, 2-4 hrs/day, > 95 Deg. F'
    write(*,3) '3) Cold acclimated'
    write(*,3) ' '
    write(*,1)
    write(*,*) 'Please enter 1, 2, or 3: >'
    read(*,*) ACCLEV

    if ((ACCLEV .NE. 1) .AND. (ACCLEV .NE. 2) .AND. ACCLEV .NE. 3) then
        write(*,5)
        GOTO 40
    end if

```

```

end if

41  write(*,2) 'Please choose a type of exercise from the
    + list below:'
    write(*,1)
    write(*,*) 'Walking, running, cycling, skiing, basketball'
    write(*,*) 'boxing, soccer, rowing, tennis, circuit training,'
    write(*,*) 'field hockey, football, squash, or aerobics.'
    read(*,4) EXDESC

    if ((EXDESC .NE. 'running') .AND.
    + (EXDESC .NE. 'walking') .AND.
    + (EXDESC .NE. 'cycling') .AND.
    + (EXDESC .NE. 'skiing') .AND.
    + (EXDESC .NE. 'basketball') .AND.
    + (EXDESC .NE. 'boxing') .AND.
    + (EXDESC .NE. 'soccer') .AND.
    + (EXDESC .NE. 'rowing') .AND.
    + (EXDESC .NE. 'tennis') .AND.
    + (EXDESC .NE. 'circuit training') .AND.
    + (EXDESC .NE. 'field hockey') .AND.
    + (EXDESC .NE. 'football') .AND.
    + (EXDESC .NE. 'squash') .AND.
    + (EXDESC .NE. 'aerobics')) then
        write(*,5)
        GOTO 41
    end if

    if ((EXDESC .EQ. 'walking') .OR. (EXDESC .EQ. 'running')) then
42  write(*,2) 'Please enter your speed (1 - 16 miles/hr): >'
        read(*,*) VMPH
        if ((VMPH .LE. 0.0) .OR. (VMPH .GT. 16.0)) then
            write(*,5)
            GOTO 42
        end if
    else if (EXDESC .EQ. 'cycling') then
43  write(*,2) 'Please enter your speed (7 - 25 miles/hr): >'
        read(*,*) VMPH
        if ((VMPH .LT. 7.0) .OR. (VMPH .GT. 25.0)) then
            write(*,5)
            GOTO 43
        end if
    else if (EXDESC .EQ. 'skiing') then
44  write(*,2) 'Please enter your speed (2.5 - 8.8 miles/hr): >'
        read(*,*) VMPH
        if ((VMPH .LT. 2.5) .OR. (VMPH .GT. 8.8)) then
            write(*,5)
            GOTO 44
        end if
    else if (EXDESC .EQ. 'boxing') then
45  write(*,2) 'In a ring (ring) or sparring (spar)? >'

```

```

read(*,4) BOXANS
  if ((BOXANS .NE. 'ring') .AND. (BOXANS .NE. 'spar')) then
    write(*,5)
    GOTO 45
  end if
end if

```

```

*****
*
* SECTION 2: This section defines/calculates constants and initial
* values based on user input.
*
*****

```

```

CA = 0.006949
CB = 0.86
GLU = 0.0
HVAP = 10.39
NUMDAT = 0
TSWEAT = 0.0

```

C — Calculate total height (cm); convert weight to kg, temperature  
C to Deg. C, wind velocity to m/s, and velocity created by user to m/s.

```

HT = (12*FT + IN)*2.54
MKG = WTLBS * 0.4536
TIC = (TIF - 32.0)/1.8
WMETPS = 0.447 * WMPH
VMETPS = 0.447 * VMPH

```

C — Calculate surface area of body used on various mechanisms of  
C heat transfer as a percentage of body surface area

```

BSA = 0.00718 * (MKG**0.425) * (HT**0.725)
AC = 0.94*BSA
AR = 0.78*BSA
AV = 0.15*BSA

```

```

PA = PSAT(TIC)
YA = RHUM * PA / 760.0
PSI = PSAT(40)

```

C — Calculate basal metabolism (kcal/day) based on gender,  
C age, weight, and height

```

if ((GENDER .EQ. 'F') .OR. (GENDER .EQ. 'f')) then
  BASAL = 655.1 + 9.563*MKG + 1.850*HT - 4.676*AGE
else if ((GENDER .EQ. 'M') .OR. (GENDER .EQ. 'm')) then
  BASAL = 66.5 + 13.75*MKG + 5.003*HT - 6.775*AGE
end if

```

BASAL = BASAL / (24.0 \* 60.0)      ! Change units to kcal/min

- C    — Initial values for energy loss terms based on basal metabolism

QRES = 0.1 \* BASAL  
 QRAD = 0.6 \* BASAL  
 QEVAP = 0.1 \* BASAL  
 QCONV = 0.2 \* BASAL

- C    — Calculate initial skin temperature based on environmental  
 C    temperature and body core temperature

$T_{SCO} = T_{BC} - (T_{BC} - T_{IC}) / 2.0$

- C    — Determine volume of the body in cubic meters taking body build  
 C    into account

$BCM = WTLBS * 0.07 / 154.0$

if (FRAME .EQ. 'small') then  
   BCMB = BCM \* 0.75  
 else if (FRAME .EQ. 'medium') then  
   BCMB = BCM \* 1.00  
 else if (FRAME .EQ. 'large') then  
   BCMB = BCM \* 1.25  
 end if

- C    — Determine clothing factor

if (ICLO.EQ.1) then  
   CLOTHES = 'Shorts only'  
   CLO = 1.0  
 else if (ICLO.EQ.2) then  
   CLOTHES = 'Shorts and short-sleeve shirt or singlet'  
   CLO = 0.70  
 else if (ICLO.EQ.3) then  
   CLOTHES = 'Shorts and long-sleeve shirt'  
   CLO = 0.55  
 else if (ICLO.EQ.4) then  
   CLOTHES = 'Legs covered and long-sleeve shirt'  
   CLO = 0.30  
 else if (ICLO.EQ.5) then  
   CLOTHES = 'Legs, arms, hands, and head all covered'  
   CLO = 0.25  
 end if

- C    — Set gain in sweat rate equation based on level of training

if (ACTLEV .EQ. 1) then  
   GAIN1 = 1.65  
 else

GAIN1 = 1.0  
end if

C — Define initial body core temperature (deg. C) and maximum sweat  
C rate (kg/hr) based on level of acclimatization

if ((ACCLEV .EQ. 2) .AND. (ACTLEV .EQ. 1)) then  
MAXSR = 4.0  
TBC = 36.7  
else  
MAXSR = 1.5  
TBC = 37.0  
end if

C — Calculate glycogen content in muscles in mmoles using typical  
C values for muscle distribution in the body and glycogen density  
C in the muscles.

QUAD = (0.7 \* 0.665 \* 0.1101 \* BCMB \* 17750 \* 5.5)  
HAM = (0.3 \* 0.665 \* 0.1101 \* BCMB \* 17750 \* 5.5)  
BICEP = (0.5 \* 0.0241 \* 0.70 \* BCMB \* 17750 \* 5.5)  
TRICEP = (0.5 \* 0.70 \* 0.0241 \* BCMB \* 17750 \* 5.5)  
CALF = (0.046 \* 0.55 \* 0.6 \* BCMB \* 17750 \* 5.5)

C — Calculate metabolic rate for the type of exercise selected

if ((EXDESC .EQ. 'walking') .OR. (EXDESC .EQ. 'running')) then  
if ((VMPH .GT. 0.0) .AND. (VMPH .LT. 2.0)) then  
MDOT = 125.0  
else if ((VMPH .GE. 2.0) .AND. (VMPH .LT. 3.0)) then  
MDOT = 151.0 + (VMPH - 2.0) \* 82.0  
else if ((VMPH .GE. 3.0) .AND. (VMPH .LT. 4.0)) then  
MDOT = 233.0 + (VMPH - 3.0) \* 133.0  
else if ((VMPH .GE. 4.0) .AND. (VMPH .LT. 5.0)) then  
MDOT = 366.0 + (VMPH - 4.0) \* 210.0  
else if ((VMPH .GE. 5.0) .AND. (VMPH .LT. 6.0)) then  
MDOT = 576.0 + (VMPH - 5.0) \* 46.0  
else if ((VMPH .GE. 6.0) .AND. (VMPH .LT. 8.0)) then  
MDOT = 622.0 + (VMPH - 6.0) \* 43.5  
else if ((VMPH .GE. 8.0) .AND. (VMPH .LT. 10.0)) then  
MDOT = 709.0 + (VMPH - 8.0) \* 172.5  
else if ((VMPH .GE. 10.0) .AND. (VMPH .LT. 12.0)) then  
end if

MDOT = MDOT \* WTLBS/154.0

if (WMPH .EQ. 1.0) then  
VELTOT = VMETPS  
end if

if ((WW .EQ. 'A') .OR. (WW .EQ. 'a')) then



```

VELTOT = VMETPS + WMETPS
else if ((WW.EQ. 'F') .OR. (WW.EQ. 'f')) then
  VELTOT = ABS(VMETPS - WMETPS)
else if ((WW.EQ. 'N') .OR. (WW.EQ. 'n')) then
  VELTOT = VMETPS
end if

```

- C —Calculate heat transfer coefficients for various mechanisms of  
C heat transfer based on the clothing factor and velocity

```

HC = CLO*6.4*VELTOT**0.67
HR = 4.3*CLO
HV = 11.9*CLO*VELTOT**0.6
KG = 0.0206332 * CLO*VELTOT**0.6

```

- C — Calculate rate of air intake (mole/hr), and rate of  
C oxygen required for exercise (l/min)

```

VAIRL = 0.0264 * MDOT - 0.714
AIRMOL = VAIRL * 60.0 / (0.08206 * (TIC + 273.15))
VOL = 0.002768 * MDOT - 0.07164

```

- C — Calculate maximal oxygen capacity for users who do not know their  
C best recent time for the mile run. Calculation is based on user's  
C activity, age, and weight.

```

if ((ANS.EQ. 'N') .OR. (ANS.EQ. 'n') .AND. ACTLEV.EQ. 1) then
  VOMAX = (59.943 - 0.346*AGE) * MKG/1000.0
else if ((ANS.EQ. 'N') .OR. (ANS.EQ. 'n') .AND. ACTLEV.EQ. 2) then
  VOMAX = (103.43 - 1.257*AGE) * MKG/1000.0
end if

```

```

MILE = MIN + SEC/60.0
VOMAX = (1608.0 + 30.0*MILE)/(5.0*(MILE + 1.0))*MKG/1000.0

```

- C — Calculate percent maximum oxygen capacity required for  
C level of exercise selected

```

PVO = VOL / VOMAX * 100.0
IPVO = PVO
write(*,7) 'You are exercising at ',IPVO,' % of your capacity.'
write(*,98)

```

- C — Calculate rate of glucose or carbohydrate consumption  
C at level of exercise selected

```

SGLU = 0.005827*PVO+0.00004545*(PVO**2)+0.000001667*(PVO**3)

if (ACTLEV.EQ. 1) SGLU = 0.75*SGLU

```

```
*****
*
* SECTION 3: This section calculates change in body temperature,
* weight loss, and carbohydrate usage with time. Data are written
* to data files every 5 minutes and printed to the screen every 15
* minutes.
*
*****
```

```
DO 150 TT = 15,300,15
```

```
DO 111 j = 1,3
```

```
DO 110 k = 0,4,9,0,1
```

```
  if (TT .EQ. 15 .AND. j .EQ. 1 .AND. k .EQ. 0) then
```

```
    TSC = TSCO
```

```
    TTSC = TSCO
```

```
  end if
```

```
C  — Calculate thermal conductivity as function of body temperature
C  to account for vasoconstriction (TBC < 37 Deg. C) or vasodilation
C  (TBC > 37 Deg. C)
```

```
  if (TBC .LT. 37.0) then
```

```
    SKO = 0.5*(1.0 - (37.0 - TBC)/6.0)
```

```
  else
```

```
    SKO = 0.5*(1.0 + (TBC - 37.0)/3.0)
```

```
  end if
```

```
C  — Calculate new skin temperatures
```

```
    TNSC = TBC - ((QRES + QEVAP + QCONV + QRAD)/10.0)/(1.8*SKO)
```

```
C  — Average last three skin temperatures
```

```
    TSC = (TSC + TTSC + TNSC)/3.0
```

```
    TTSC = TNSC
```

```
    TICL = TIC + 1.0
```

```
    TBCL = TBC - 0.5
```

```
C  — Skin temperature cannot be < 1 Deg. C more than
C  environmental temperature
```

```
  if (TSC .LT. TICL) TSC = TICL
```

```
C  — Skin temperature cannot be > 1/2 Deg. C less than body
C  core temperature
```

```
  if (TSC .GT. TBCL) TSC = TBCL
```

```
  PS = PSAT(TSC)
```

- C — Calculate rate of evaporative mass transfer

$$Z = KG \cdot AV \cdot (PS - RHUM \cdot PA)$$

- C — If core temperature < 37 Deg. C water loss is determined  
C by the rate of evaporation

$$\text{if (TBC .LT. 37.0) DSWEAT} = Z$$

- C — Determine level of dehydration to modify slope of DWEAT vs. TBC  
C relationship used in determining sweat rate. The gains  
C defined with respect to a given level of dehydration are NOT  
C specifically provided in literature, but have been arbitrarily  
C estimated using a hypothesized trend.

if (TSWEAT .LT. 0.01\*MKG) then

$$GAIN2 = 1.0$$

else if ((TSWEAT .GE. 0.01\*MKG).AND.(TSWEAT .LT. 0.02\*MKG)) then

$$GAIN2 = 0.95$$

else if ((TSWEAT .GE. 0.02\*MKG).AND.(TSWEAT .LT. 0.03\*MKG)) then

$$GAIN2 = 0.85$$

else if ((TSWEAT .GE. 0.03\*MKG).AND.(TSWEAT .LT. 0.04\*MKG)) then

$$GAIN2 = 0.75$$

else if ((TSWEAT .GE. 0.04\*MKG).AND.(TSWEAT .LT. 0.05\*MKG)) then

$$GAIN2 = 0.65$$

end if

- C — Call subroutine to calculate sweat rate (water loss rate)

$$DSWEAT = \text{WATERLOSS}(TSC, TBC, MDOT, GAIN1, GAIN2)$$

if (DSWEAT .GT. MAXSR) DSWEAT = MAXSR

$$SWEAT = DSWEAT / 600.0 \quad !\text{Convert rate to kg/6 sec}$$

- C — Calculate energy lost through respiration, evaporation,  
C convection and radiation

$$PEXP = PSAT(TBC)$$

$$YEXP = PEXP / 760.0$$

$$QRES = \text{AIRMOL} \cdot (CA \cdot (TBC - TIC) + HVAP \cdot (YEXP - YA)) / 60.0$$

$$QEVAP = HV \cdot AV \cdot (PS - RHUM \cdot PA) / 60.0$$

$$QCONV = HC \cdot AC \cdot (TSC - TIC) / 60.0$$

$$QRAD = HR \cdot AR \cdot (TSC - TIC) / 60.0$$

$$QTOT = QRES + QEVAP + QCONV + QRAD - MDOT / 60.0$$

$$EMAX = QEVAP \cdot 0.1$$

! Convert rate to kcal/6 sec

$$DRIP = EMAX / 3.0$$

! Determine point at which run-off occurs

! (1/3 max evaporative capacity)

- C — Calculate body temperature change in 6 seconds by using

- C dividing new rate of heat loss and new body weight

$$DTB = -(QTOT/10.0)/((MKG - TSWEAT)*CB)$$

- C — Calculate new body core temperature

$$TBC = TBC + DTB$$

- C — Add water loss in current period to the previous water loss.

- C If the sweat rate is greater than or equal to 1/3 maximum evaporative  
C capacity then loss of sweat can occur by dripping. If the sweat rate  
C is less than 1/3 EMAX then loss of water occurs by evaporation.

```

if (SWEAT .GE. DRIP) then
  TSWEAT = TSWEAT + SWEAT
else
  TSWEAT = TSWEAT + Z/600.0
end if

```

```

if (j .eq. 1) then
  TS = k+(TT-15.0)
else if (j .eq. 2) then
  TS = (5.0 + k)+(TT-15.0)
else if (j .eq. 3) then
  TS = (10.0 + k)+(TT-15.0)
end if

```

! Time counter used in output

- C — Calculate the amount of glucose used in period

$$DGLU = SGLU * 1.030 / 10.0$$

- C — Calculate total glucose usage

$$GLU = GLU + DGLU$$

- C — Determine whether maximum glucose usage has been surpassed

```

if ((EXDESC .EQ. 'running') .OR. (EXDESC .EQ. 'walking')) then
  if (GLU .GE. CALF) then
    write(*,100)
    write(*,101)
    GOTO 275
  end if
  else if (EXDESC .EQ. 'cycling') then
    if ((GLU .GE. (0.7 * QUAD)) .OR.
+ (GLU .GE. (0.3 * (BICEP + TRICEP)))) then
      write(*,100)
      write(*,101)
      GOTO 275
    end if
    else if (EXDESC .EQ. 'rowing') then

```

```

      if ((GLU .GE. (0.5 * QUAD))
+ .OR. (GLU .GE. (0.5 * BICEP))) then
        write(*,100)
        write(*,101)
        GOTO 275
      end if
      else if (EXDESC .EQ. 'circuit training') then
        if ((GLU .GE. (0.2 * QUAD)) .OR. (GLU .GE. (0.2 * BICEP))
+ .OR. (GLU .GE. (0.2 * HAM)) .OR. (GLU .GE. (0.2 * TRICEP))
+ .OR. (GLU .GE. (0.2 * CALF))) then
          write(*,100)
          write(*,101)
          GOTO 275
        end if
      else if (.NOT. ((EXDESC .EQ. 'running') .OR.
+ (EXDESC .EQ. 'walking') .OR. (EXDESC .EQ. 'cycling')
+ .OR. (EXDESC .EQ. 'rowing')
+ .OR. (EXDESC .EQ. 'circuit training')))) then
        if (GLU .GE. 92.7) then
          write(*,100)
          write(*,101)
          GOTO 275
        end if
      end if
end if

```

C — Determine if hypothermia has been achieved

```

if (TBC .LE. 34.0) then
  write(*,1) 'HYPOTHERMIA!!!'
  write(*,*) 'Body core temperature has fallen below 92 Deg. F.'
  GOTO 275
end if

```

C — Determine if hypothermia has been achieved

```

if (TBC .GE. 40.0) then
  write(*,1) 'HYPEROTHERMIA!!!'
  write(*,*) 'Body core temperature has exceeded 104 Deg. F.'
  GOTO 275
end if

```

C — Determine if dehydration limit has been exceeded

```

if (TSWEAT .GE. 0.05*MKG) then
  write(*,1) 'DEHYDRATION!!!'
  write(*,*) 'Loss of body water exceeds 5% total body weight.'
  GOTO 275
end if

```

C — Determine if exercise duration has been exceeded

```

    if (TT .GT. TTMAX) then
      write(*,1) 'Exercise duration is complete!'
      GOTO 275
    end if

    T = TS + 0.1

110  CONTINUE

C    — Write data to output file

    FTSC = 1.8 * TSC + 32.0
    CBT = 1.8 * TBC + 32.0
    HD = -QTOT
    CBW = (MKG - TSWEAT) * 2.2046
    CU = GLU * 100.0/92.7

    open (unit = 1,type = 'new',name = 'BODYTEMP.DAT')
    open (unit = 2,type = 'new',name = 'QTOT.DAT')
    open (unit = 3,type = 'new',name = 'BODYWT.DAT')
    open (unit = 4,type = 'new',name = 'SKINTEMP.DAT')

    write(1,99) T,CBT
    write(2,99) T,HD
    write(3,99) T,CBW
    write(4,99) T,FTSC

C    — Count number of data pts.

    NUMDAT = NUMDAT + 1

111  CONTINUE

C    — Print values to the screen every 15 min.

270  write(*,6) 'AFTER ',T,' MINUTES:'
      write(*,1)
      write(*,202) 'Rate of heat loss by respiration = ',QRES,' kcal/min'
      write(*,202) 'Rate of heat loss by evaporation = ',QEVAP,' kcal/min'
      write(*,202) 'Rate of heat loss by convection = ',QCONV,' kcal/min'
      write(*,202) 'Rate of heat loss by radiation = ',QRAD,' kcal/min'
      write(*,202) 'Heat accumulation in body = ',HD,' kcal/min'
      write(*,1)
      write(*,201) 'Skin temperature = ',FTSC,' Deg. F'
      write(*,201) 'Current body temperature = ',CBT,' Deg. F'
      write(*,201) 'Current body weight = ',CBW,' lbs'
      write(*,269)
      read(*,*)

C    — Continue simulation if hyperthermia, hypothermia, dehydration or
C    exhaustion have not been reached

```

150 CONTINUE

275 write(\*,7) 'Total exercise duration = ',T,' min'  
 write(\*,269)  
 read(\*,\*)

```
*****
*
*   SECTION 4: This section calls subroutines FUELUSE, PRINTAB, PLOTDATA
*   to estimate fuel usage, print a summary and plot data from the
*   simulation, respectively.
*
*****
```

CALL FUELUSE(TT,VOL,PVO,TOTCAL,CHCAL,LIPCAL,CHUSED,LIPUSED)

CALL PRINTAB

```

      write(*,2) 'Would you like to plot any of the following results
+from the simulation run?'
      write(*,1)
280   write(*,3) '1) Body Temperature vs. Time'
      write(*,3) '2) Heat Loss vs. Time '
      write(*,3) '3) Body Weight vs. Time'
      write(*,3) '4) Skin Temperature vs. Time'

285   write(*,1)
      write(*,*) 'If YES, please enter Y; if NO, please enter N: >'
      read (*,4) ANS

      if ((ANS .NE. 'Y') .AND. (ANS .NE. 'N') .AND. (ANS .NE. 'y')
+      .AND. (ANS .NE. 'n')) then
        write(*,5)
        GOTO 285
      end if

      if ((ANS .EQ. 'Y') .OR. (ANS .EQ. 'y')) then
        call PLOTDATA(NUMDAT)
      else
        GOTO 300
      end if

300   write(*,2) 'Would you like to test some other conditions?'
301   write(*,*) 'If YES, please enter Y; if NO, please enter N: >'
      READ (*,4) ICASE

      if ((ICASE .NE. 'Y') .AND. (ICASE .NE. 'y') .AND.
+      (ICASE .NE. 'N') .AND. (ICASE .NE. 'n')) then
        write(*,5)
        GOTO 301
```

```

else if ((ICASE .EQ. 'Y') .OR. (ICASE .EQ. 'y')) then
  close (1)
  close (2)
  close (3)
  close (4)
  GOTO 14
end if

```

```

1  format(/,1X,A)
2  format(/,1X,A)
3  format(1X,TR5,A)
4  format(A)
5  format(/,1X,'You have entered an invalid response,
+ please try again.',/)
6  format (/,1X,A,F5.1,A)
7  format (/,1X,A,F5.1,A)
98 format(1X,60('-',/))
99 format (1X,F5.1,F10.2)
100 format(1X,'EXHAUSTION!!!')
101 format(1X,'You have depleted the carbohydrate stores in the
+ working muscle(s).')
201 format (1X,A,F7.1,A)
202 format (1X,A,F7.2,A)
269 format(/,1X,TR20,'Please press <RETURN> to continue.',/ / /)

```

```

STOP
END

```

```

*****
*
*   This section contains FUNCTION and SUBROUTINE programs to print a
*   summary table, plot the data, calculate saturated water vapor
*   pressure, sweat rates, and fuel use.
*
*****

```

```

*****
*----- SUBROUTINE PRINTAB prints a table of results after the -----*
*----- simulation is complete. -----*
*****

```

#### SUBROUTINE PRINTAB

```

real  WTLBS,MKG,RHUM,MDOT,VMPH,TIF,CBW,CBT
real  TOTCAL,CHCAL,LIPCAL,LIPUSED,CHUSED,FTSC,VOL

```

```

character NAME*50,EXDESC*50,CLOTHES*50
integer  AGE,FT,IN,MIN,SEC,TT,ACTLEV

```

```

common NAME,FT,IN,WTLBS,AGE,CLOTHES,MIN,SEC,ACTLEV,EXDESC
common MDOT,VOL,VMPH,TIF,RHUM,WMPH,TS,CBW,CBT,FTSC,TOTCAL

```



common CHCAL,LIPCAL,CHUSED,LIPUSED

```

write(*,9)
write(*,*) 'SUMMARY OF EXERCISE SIMULATION FOR: >'
write(*,*) NAME

write(*,2) '— Characteristics of the Athlete'
write(*,6) 'Height: ',FT,' ft. ',IN,' inches'
write(*,4) 'Weight: ',WTLBS,' lbs.'
write(*,6) 'Age: ',AGE,' years'
write(*,*) 'Clothing: ',CLOTHES
write(*,1)
write(*,6) 'Best recent time for the mile: ',MIN,' min ',SEC,' sec'
write(*,*) 'Where: 0 - not available'
write(*,1)
write(*,8) 'Activity level = ',ACTLEV
write(*,*) 'Where: 1 - Active, 2 - Inactive'
write(*,10)
read(*,*)

```

```

write(*,2) '— Exercise Data'
write(*,3) EXDESC
write(*,1)
write(*,4) 'Metabolic rate    = ',MDOT,' kcal/hr'
write(*,4) 'Oxygen Consumption = ',VOL,' liters oxygen/min'
write(*,4) 'Exercise Velocity = ',VMPH,' miles/hr (0 = N/A)'
write(*,2) '— Environmental Conditions'
write(*,4) 'Air temperature = ',TIF,' Deg. F'
write(*,5) 'Relative humidity = ',RHUM
write(*,4) 'Wind velocity    = ',WMPH,' miles/hr'
write(*,10)
read(*,*)

```

```

write(*,2) '— Final Simulation Values'
write(*,7) 'Duration of Exercise = ',TS,' min'
write(*,4) 'Final body weight = ',CBW,' lbs'
write(*,4) 'Final body temp. = ',CBT,' Deg. F'
write(*,4) 'Final skin temp. = ',FTSC,' Deg. F'

```

```

write(*,2) '— Fuel Use'
write(*,4) 'Total energy spent = ',TOTCAL,' kcal'
write(*,4) ' - Carbohydrates = ',CHCAL,' kcal'
write(*,4) ' - Fats          = ',LIPCAL,' kcal'
write(*,1)
write(*,4) 'Carbohydrates used: ',CHUSED,' grams'
write(*,4) 'Fats used:          ',LIPUSED,' grams'
write(*,10)
read(*,*)

```

1      format(1X, /)

```

2   format (//,1X,A,/)
3   format (1X,TR5,A)
4   format (1X,A,F7.1,A)
5   format (1X,A,F7.2,A)
6   format (1X,A,I3,A,I3,A)
7   format (1X,A,TR2,F5.1,A)
8   format (1X,A,I2)
9   format (1X,60('-',)/)
10  format (//,1X,TR20,'Please press <Return> to continue.',/)

```

```

RETURN
END

```

```

*****
*----- SUBROUTINE PLOTDATA plots data calculated in the simulation. -----*
*****

```

```

SUBROUTINE PLOTDATA(NUMDAT)

```

```

real    LINE(0:100),STAR,SCALE,X(100),XMAX,XMIN
real    Y(100),YMAX,YMIN
integer CHOICE,NUMDAT,PF
character  FILENAME*15,PRINTFILE*15,YVAR*25,XVAR*15

```

```

290  write(*,1)
      read(*,*) CHOICE

      if (CHOICE .LE. 4 .AND. CHOICE .GE. 1) then
        XVAR = 'TIME (min)'
      else
        write(*,2)
        GOTO 290
      end if

      if (CHOICE .EQ. 1) then
        FILENAME = 'BODYTEMP.DAT'
        PRINTFILE = 'BODYTEMP.TXT'
        PF = 5
        YVAR = 'BODY TEMP. (Deg. F)'
      else if (CHOICE .EQ. 2) then
        FILENAME = 'QTOT.DAT'
        PRINTFILE = 'QTOT.TXT'
        PF = 6
        YVAR = 'HEAT LOSS (kcal/min)'
      else if (CHOICE .EQ. 3) then
        FILENAME = 'BODYWT.DAT'
        PRINTFILE = 'BODYWT.TXT'
        PF = 7
        YVAR = 'BODY WEIGHT (lbs)'
      else if (CHOICE .EQ. 4) then
        FILENAME = 'SKINTEMP.DAT'

```

```

PRINTFILE = 'SKINTEMP.TXT'
PF = 8
YVAR = 'SKIN TEMP. (Deg. F)'
end if

```

C — Input data

```

open (unit = CHOICE, status = 'old', file = FILENAME)
rewind (CHOICE)
open (unit = PF, status = 'new', file = PRINTFILE)
rewind (PF)

do 6 i = 1, NUMDAT
  read (CHOICE, 12) X(i), Y(i)
6  continue

  YMAX = Y(1)
  YMIN = Y(1)

  do 9 i = 1, NUMDAT
    if (Y(i) .LT. YMIN) YMIN = Y(i)
    if (Y(i) .GT. YMAX) YMAX = Y(i)
9  continue

  SCALE = YMAX - YMIN

  do 10 i = 0, 55
    LINE(i) = ''
10 continue

```

C — Plot data

```

write(*, 3) PRINTFILE
write(PF, 4) 'X', 'Y'
write(*, 4) 'X', 'Y'

do k = 1, NUMDAT
  STAR = (Y(k) - YMIN)*55.0/SCALE
  LINE(STAR) = '*'
  write(PF, 5) X(k), Y(k), (LINE(i), i = 0, 55)
  write(*, 5) X(k), Y(k), (LINE(i), i = 0, 55)
  LINE(STAR) = ''
end do

write(PF, 13)
write(*, 13)
write(PF, 14) XVAR, YVAR
write(*, 14) XVAR, YVAR

write(*, *) 'Would you like to plot some other data?'
295 write(*, *) 'If YES, please enter Y; if NO, please enter N: >'

```

```

READ (*,16) ICASE

if ((ICASE .NE. 'Y') .AND. (ICASE .NE. 'y') .AND.
+ (ICASE .NE. 'N') .AND. (ICASE .NE. 'n')) then
    write(*,5)
    GOTO 295
end if

if ((ICASE .EQ. 'N') .OR. (ICASE .EQ. 'n')) then
    RETURN
else
    close (PF)
    write(*,11) '1) Body Temperature vs. Time'
    write(*,15) '2) Heat Loss vs. Time '
    write(*,15) '3) Body Weight vs. Time'
    write(*,15) '4) Skin Temperature vs. Time'
    GOTO 290
end if

1   format (/,1X,'Please enter 1, 2, 3, or 4: >')
2   format (1X,'You have entered an invalid response,
+ please try again.',/)
3   format (/,1X,'The output file will be named ',A,/)
4   format (3X,A1,TR7,A1,TR8,56('-'))
5   format (1X,F5.1,F10.2,TR3,'|',56A1,'|')
11  format (/,1X,A)
12  format (1X,F5.1,F10.2)
13  format (1X,TR19,56('-'),/)
14  format (1X,'Where: ',X = ',A10,4X,'Y = ',A20,/)
15  format (1X,A)
16  format (A)

RETURN
END

```

```

*****
*----- FUNCTION PSAT calculates saturated vapor pressure (mmHg) of -----*
*----- water at given temperatures using the Antoine equation. -----*
*****

```

FUNCTION PSAT(T)

real T,A,B,C

C — Antoine constants for water

A = 8.10765

B = 1750.286

C = 235.0

PSAT = 10\*\*(A - B/(T+C))

RETURN  
END

\*\*\*\*\*  
\*----- FUNCTION WATERLOSS calculates rate of water loss (evaporation -----\*  
\*----- and runoff) for given skin temperatures and metabolic rates. -----\*  
\*\*\*\*\*

FUNCTION WATERLOSS(TSC,TBC,MDOT,GAIN1,GAIN2)

real TBC,TSC,MDOT,GAIN1,GAIN2

GAIN = GAIN1\*GAIN2

if (MDOT .LE. 300.0) then  
  DSWEAT = 0.046122\*GAIN\*TBC - 1.16399  
else if (MDOT .LE. 500.0 .AND. MDOT .GT. 300.0) then  
  if (TSC .LE. 33.0) then  
    DSWEAT = 0.063091\*GAIN\*TBC - 1.53415  
  else  
    DSWEAT = 0.295611\*GAIN\*TBC - 9.53531  
  end if  
else if (MDOT .LE. 700.0 .AND. MDOT .GT. 500.0) then  
  if (TSC .LE. 33.4) then  
    DSWEAT = 0.091916\*GAIN\*TBC - 2.21063  
  else  
    DSWEAT = 0.512109\*GAIN\*TBC - 16.9846  
  end if  
else if (MDOT .LE. 900.0 .AND. MDOT .GT. 700.0) then  
  if (TSC .LE. 32.0) then  
    DSWEAT = 0.223172\*GAIN\*TBC - 6.03852  
  else  
    DSWEAT = 0.390976\*GAIN\*TBC - 11.8576  
  end if  
else if (MDOT .LE. 1100.0 .AND. MDOT .GT. 900.0) then  
  DSWEAT = 0.256577\*GAIN\*TBC - 5.75055  
else if (MDOT .LE. 1300.0 .AND. MDOT .GT. 1100.0) then  
  if (TSC .LE. 29.0) then  
    DSWEAT = 0.439115\*GAIN\*TBC - 12.3871  
  else  
    DSWEAT = 0.314289\*GAIN\*TBC - 8.09200  
  end if  
else if (MDOT .LE. 1500.0 .AND. MDOT .GT. 1300.0) then  
  if (TSC .LE. 28.6) then  
    DSWEAT = 0.69908\*GAIN\*TBC - 21.2381  
  else  
    DSWEAT = 0.227225\*GAIN\*TBC - 4.99327  
  end if  
else if (MDOT .LE. 1700.0 .AND. MDOT .GT. 1500.0) then  
  DWEAT = 0.053090\*GAIN\*TBC + 1.639657

end if

WATERLOSS = DSWEAT

RETURN

END

\*\*\*\*\*  
 \*----- SUBROUTINE FUELUSE calculates (using fuel consumption data) -----\*  
 \*----- total energy spent (kcal) and amount (grams) of carbohydrates and -----\*  
 \*----- lipids oxydized for a given duration and intensity of exercise.-----\*  
 \*\*\*\*\*

SUBROUTINE FUELUSE(TT,VOL,PVO,TOTCAL,CHCAL,LIPCAL,CHUSED,LIPUSED)

real R,CALEQ,TOTVOL,TOTCAL,CHFRAC,CHCAL,PVO

real VOL,LIPCAL,CHEQ,LIPEQ,CHUSED,LIPUSED

integer TT

\*\*\*\*\*  
 \*  
 \* SUBROUTINE VARIABLES \*  
 \*  
 \* VARIABLE DESCRIPTION \*  
 \*  
 \* CALEQ Calorific equivalent of 1 liter of oxygen consumed \*  
 \* CHCAL Calories derived from carbohydrates \*  
 \* CHEQ Equivalent carbohydrates oxydized (grams) per \*  
 \* 1 liter oxygen consumed \*  
 \* CHFRAC Percentage calories derived from carbohydrates \*  
 \* CHUSED Total carbohydrate oxydized (grams) \*  
 \* LIPCAL Calories derived from lipids \*  
 \* LIPEQ Equivalent lipids oxydized (grams) per \*  
 \* 1 liter oxygen consumed \*  
 \* LIPUSED Total lipids oxydized (grams) \*  
 \* PVO Athlete's percent maximal oxygen capacity at \*  
 \* R Nonproteic respiratory quotient as function of PVO \*  
 \* and duration of exercise \*  
 \* TOTVOL Total volume of oxygen consumed \*  
 \* TOTCAL Total kcal utilized \*  
 \* TT Duration of exercise (min) \*  
 \* VOL Oxygen consumption at given metabolic rate \*  
 \* exercise level selected \*  
 \*\*\*\*\*

C Determine the nonproteic respiratory quotient equation for the duration of  
 C exercise. The equations for R are correspond to the following durations:  
 C 0 min. (ex. sprinters), 30 min., 60 min., 120 min., 180 min., 240 min. and  
 C 300 min. For durations of exercise other than these values, R is

C approximated using the equation defined at the nearest duration.

if (TT .LE. 2)	$R = 0.0021 \cdot PVO + 0.765$
if (TT .GT. 2 .AND. TT .LE. 45)	$R = 0.0021 \cdot PVO + 0.753$
if (TT .GT. 45 .AND. TT .LE. 90)	$R = 0.0022 \cdot PVO + 0.737$
if (TT .GT. 90 .AND. TT .LE. 150)	$R = 0.0020 \cdot PVO + 0.740$
if (TT .GT. 150 .AND. TT .LE. 210)	$R = 0.0019 \cdot PVO + 0.735$
if (TT .GT. 210 .AND. TT .LE. 270)	$R = 0.0020 \cdot PVO + 0.713$
if (TT .GT. 270)	$R = 0.0021 \cdot PVO + 0.769$

if (TT .GT. 300) then  
 write(\*,1) 'Maximum duration limit is 5 hours.'  
 write(\*,\*) 'Percentages of carbohydrates and fats used will be '  
 write(\*,2) 'based on this duration of exercise.'  
 end if

C — Calculate total energy expenditure.

CALEQ =  $3.813 + 1.233 \cdot R$   
 TOTVOL = TT \* VOL  
 TOTCAL = TOTVOL \* CALEQ

C — Calculate calories derived from each fuel

CHFRAC =  $(-239.32 + 340.32 \cdot R) / 100.0$   
 CHCAL = CHFRAC \* TOTCAL  
 LIPCAL =  $(1.0 - CHFRAC) \cdot TOTCAL$

C — Calculate grams of carbohydrate and lipids oxydized

CHEQ =  $-2.977 + 4.195 \cdot R$   
 CHUSED = TOTVOL \* CHEQ  
 LIPEQ =  $1.722 - 1.717 \cdot R$   
 LIPUSED = TOTVOL \* LIPEQ

1 format(/,1X,A)  
 2 format(1X,A,/)

RETURN  
 END

**APPENDIX D: SAMPLE OUTPUT**



This program is designed to inform well trained and novice athletes how long they may exercise at a certain level before one of the following conditions occur:

- a) hyperthermia: estimated core temperature surpasses 40 Deg. C (104 Deg. F)
- b) dehydration: loss of body water exceeds 5% of body weight
- c) estimated muscle glycogen supply exceeded
- d) hypothermia: estimated core temperature drops below 34 Deg. C (92 Deg. F)

Please enter your name (50 character max): >  
Megan Scherb

Gender is used in calculating basal metabolic rate.

If you are a female, please enter F;  
if you are a male, please enter M: >  
f

This program is designed for athletes between the ages of 18 and 75.

Please enter your age in years: >  
24

Please enter your height (feet, inches): >  
5.0 4.0

Please enter your body weight (60 - 300 lbs): >  
135.0

Please enter your approximate muscular build: >  
(small, medium, large)  
medium

Enter the number which best corresponds to your clothing (in addition to your shoes): >

Shorts only, enter 1.  
Shorts and short-sleeve shirt or singlet, enter 2.  
Shorts and long-sleeve shirt, enter 3.  
Legs covered and long-sleeve shirt, enter 4.  
Legs, arms, hands, and head all covered, enter 5.  
2

Please enter the air temperature (-40 to 120 Deg. F): >  
70.0

Please enter wind velocity (0 - 50 miles/hr): >  
0.0

Please enter the relative humidity as a decimal: >  
0.5

Would you like the program to:  
(1) recommend a duration of exercise?  
(2) allow you to choose a duration of exercise?

Please enter 1 or 2: >  
1

Do you know your best recent time for the mile?  
If YES, please enter Y; if NO, please enter N: >  
Y

Please enter your time for the mile (min,sec): >  
7.0 30.0

If best time for the mile is unknown, then maximum oxygen capacity is based on age and activity level.

Please select your normal level of activity:  
1) Active (well trained in distance sports)  
2) Inactive (no continuous training)

Please enter 1 or 2: >  
1

Please select level of acclimatization:  
1) Not acclimated to heat or cold  
2) Heat acclimated:  
7-10 days training, 2-4 hrs/day, > 95 Deg. F  
3) Cold acclimated

Please enter 1, 2, or 3: >  
2

Please choose a type of exercise from the list below:

Walking, running, cycling, skiing, basketball  
boxing, soccer, rowing, tennis, circuit training,  
field hockey, football, squash, or aerobics.  
running

Please enter your speed (1 - 16 miles/hr): >  
7.5

You are exercising at 60.4 % of your capacity.

-----

AFTER 15.0 MINUTES:

Rate of heat loss by respiration	=	0.40 kcal/min
Rate of heat loss by evaporation	=	2.60 kcal/min
Rate of heat loss by convection	=	4.03 kcal/min
Rate of heat loss by radiation	=	1.00 kcal/min
Heat accumulation in body	=	2.01 kcal/min

Skin temperature	=	97.8 Deg. F
Current body temperature	=	99.2 Deg. F
Current body weight	=	134.9 lbs

Please press <RETURN> to continue.

AFTER 30.0 MINUTES:

Rate of heat loss by respiration	=	0.42 kcal/min
Rate of heat loss by evaporation	=	2.71 kcal/min
Rate of heat loss by convection	=	4.19 kcal/min
Rate of heat loss by radiation	=	1.04 kcal/min
Heat accumulation in body	=	1.69 kcal/min

Skin temperature	=	98.9 Deg. F
Current body temperature	=	100.2 Deg. F
Current body weight	=	134.7 lbs

Please press <RETURN> to continue.

AFTER 45.0 MINUTES:

Rate of heat loss by respiration	=	0.43 kcal/min
Rate of heat loss by evaporation	=	2.80 kcal/min
Rate of heat loss by convection	=	4.32 kcal/min
Rate of heat loss by radiation	=	1.07 kcal/min
Heat accumulation in body	=	1.42 kcal/min

Skin temperature	=	99.8 Deg. F
Current body temperature	=	101.0 Deg. F
Current body weight	=	134.5 lbs

Please press <RETURN> to continue.

AFTER 60.0 MINUTES:

Rate of heat loss by respiration = 0.44 kcal/min  
 Rate of heat loss by evaporation = 2.88 kcal/min  
 Rate of heat loss by convection = 4.42 kcal/min  
 Rate of heat loss by radiation = 1.10 kcal/min  
 Heat accumulation in body = 1.20 kcal/min

Skin temperature = 100.5 Deg. F  
 Current body temperature = 101.6 Deg. F  
 Current body weight = 134.4 lbs

Please press <RETURN> to continue.

AFTER 75.0 MINUTES:

Rate of heat loss by respiration = 0.45 kcal/min  
 Rate of heat loss by evaporation = 2.95 kcal/min  
 Rate of heat loss by convection = 4.51 kcal/min  
 Rate of heat loss by radiation = 1.12 kcal/min  
 Heat accumulation in body = 1.01 kcal/min

Skin temperature = 101.1 Deg. F  
 Current body temperature = 102.2 Deg. F  
 Current body weight = 134.2 lbs

Please press <RETURN> to continue.

AFTER 90.0 MINUTES:

Rate of heat loss by respiration = 0.46 kcal/min  
 Rate of heat loss by evaporation = 3.00 kcal/min  
 Rate of heat loss by convection = 4.59 kcal/min  
 Rate of heat loss by radiation = 1.14 kcal/min  
 Heat accumulation in body = 0.85 kcal/min

Skin temperature = 101.6 Deg. F  
 Current body temperature = 102.7 Deg. F  
 Current body weight = 134.0 lbs

Please press <RETURN> to continue.

AFTER 105.0 MINUTES:

Rate of heat loss by respiration = 0.46 kcal/min  
 Rate of heat loss by evaporation = 3.05 kcal/min  
 Rate of heat loss by convection = 4.65 kcal/min  
 Rate of heat loss by radiation = 1.15 kcal/min  
 Heat accumulation in body = 0.72 kcal/min

Skin temperature = 102.1 Deg. F  
Current body temperature = 103.1 Deg. F  
Current body weight = 133.9 lbs

Please press <RETURN> to continue.

AFTER 120.0 MINUTES:

Rate of heat loss by respiration = 0.47 kcal/min  
Rate of heat loss by evaporation = 3.09 kcal/min  
Rate of heat loss by convection = 4.71 kcal/min  
Rate of heat loss by radiation = 1.17 kcal/min  
Heat accumulation in body = 0.61 kcal/min

Skin temperature = 102.4 Deg. F  
Current body temperature = 103.4 Deg. F  
Current body weight = 133.7 lbs

Please press <RETURN> to continue.

EXHAUSTION!!!

You have depleted the carbohydrate stores in the working muscle(s).

Total exercise duration = 132.8 min

Please press <RETURN> to continue.

-----  
SUMMARY OF EXERCISE SIMULATION FOR: >  
Megan Scherb

--- Characteristics of the Athlete

Height: 5.0 ft. 4.0 inches  
Weight: 135.0 lbs.  
Age: 24 years  
Clothing: Shorts and short-sleeve shirt or singlet

Best recent time for the mile: 7.0 min 30.0 sec  
Where: 0 - not available

Activity level = 1  
Where: 1 - Active, 2 - Inactive

Please press <Return> to continue.

## --- Exercise Data

running

Metabolic rate = 602.5 kcal/hr  
 Oxygen Consumption = 1.6 liters oxygen/min  
 Exercise Velocity = 7.5 miles/hr (0 = N/A)

## --- Environmental Conditions

Air temperature = 70.0 Deg. F  
 Relative humidity = 0.50  
 Wind velocity = 1.0 miles/hr

Please press &lt;Return&gt; to continue.

## --- Final Simulation Values

Duration of Exercise = 132.8 min  
 Final body weight = 133.6 lbs  
 Final body temp. = 103.6 Deg. F  
 Final skin temp. = 102.6 Deg. F

## --- Fuel Use

Total energy spent = 1050.2 kcal  
 - Carbohydrates = 563.4 kcal  
 - Fats = 486.8 kcal

Carbohydrates used: 136.7 grams  
 Fats used: 52.6 grams

Please press &lt;Return&gt; to continue.

Would you like to plot any of the following results from the simulation run?

- 1) Body Temperature vs. Time
- 2) Heat Loss vs. Time
- 3) Body Weight vs. Time
- 4) Skin Temperature vs. Time

If YES, please enter Y; if NO, please enter N: &gt;

Y

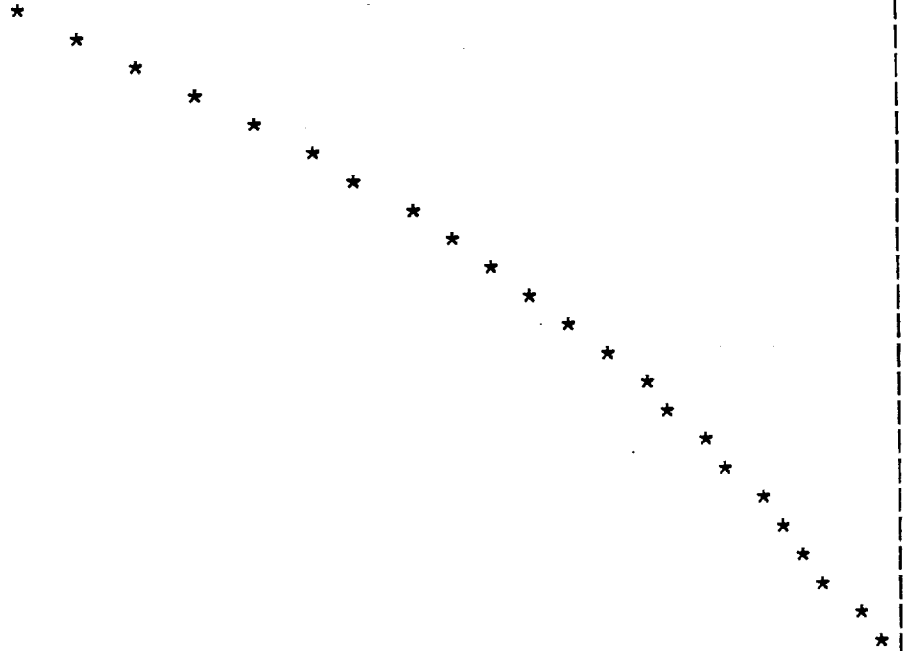
Please enter 1, 2, 3, or 4: &gt;

1

The output file will be named BODYTEMP.TXT

X	Y	
5.0	98.49	*
10.0	98.86	*
15.0	99.22	*

20.0	99.55
25.0	99.87
30.0	100.17
35.0	100.45
40.0	100.71
45.0	100.96
50.0	101.20
55.0	101.43
60.0	101.64
65.0	101.84
70.0	102.03
75.0	102.21
80.0	102.38
85.0	102.54
90.0	102.69
95.0	102.83
100.0	102.97
105.0	103.09
110.0	103.21
115.0	103.33
120.0	103.44
125.0	103.54
130.0	103.63



Where: X = TIME (min)      Y = BODY TEMP. (Deg. F)

Would you like to plot some other data?

If YES, please enter Y; if NO, please enter N: >

y

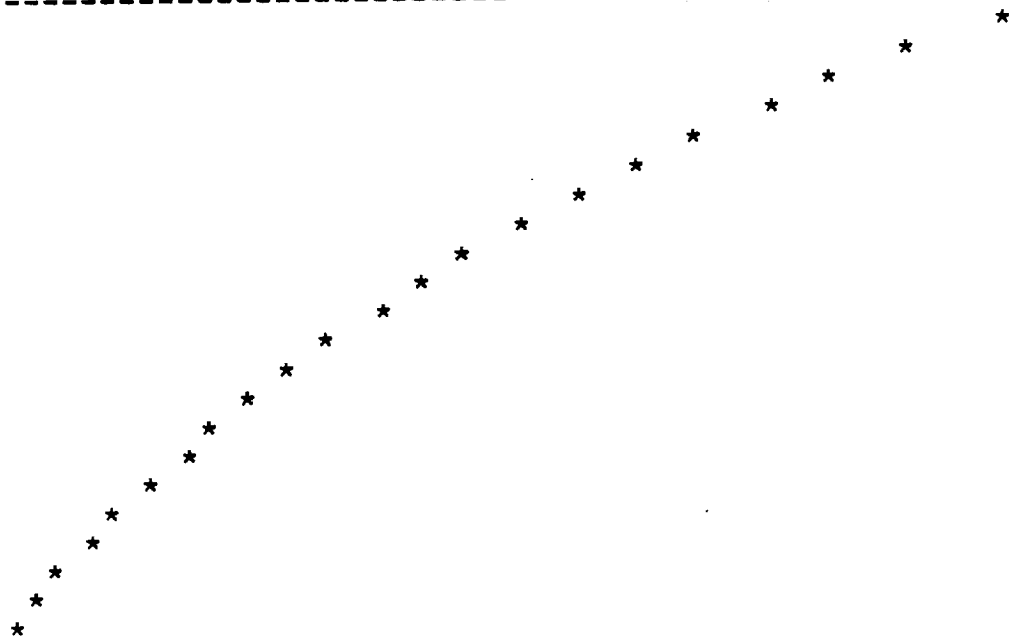
- 1) Body Temperature vs. Time
- 2) Heat Loss vs. Time
- 3) Body Weight vs. Time
- 4) Skin Temperature vs. Time

Please enter 1, 2, 3, or 4: >

2

The output file will be named QTOT.TXT

X	Y
5.0	2.27
10.0	2.14
15.0	2.01
20.0	1.90
25.0	1.79
30.0	1.69
35.0	1.60
40.0	1.51
45.0	1.42
50.0	1.34
55.0	1.27
60.0	1.20
65.0	1.13
70.0	1.07
75.0	1.01
80.0	0.96
85.0	0.90
90.0	0.85
95.0	0.81
100.0	0.76
105.0	0.72
110.0	0.68



120.0	0.61	*
125.0	0.58	*
130.0	0.54	*

Where: X = TIME (min)      Y = HEAT LOSS (kcal/min)

Would you like to plot some other data?

If YES, please enter Y; if NO, please enter N: >

Y

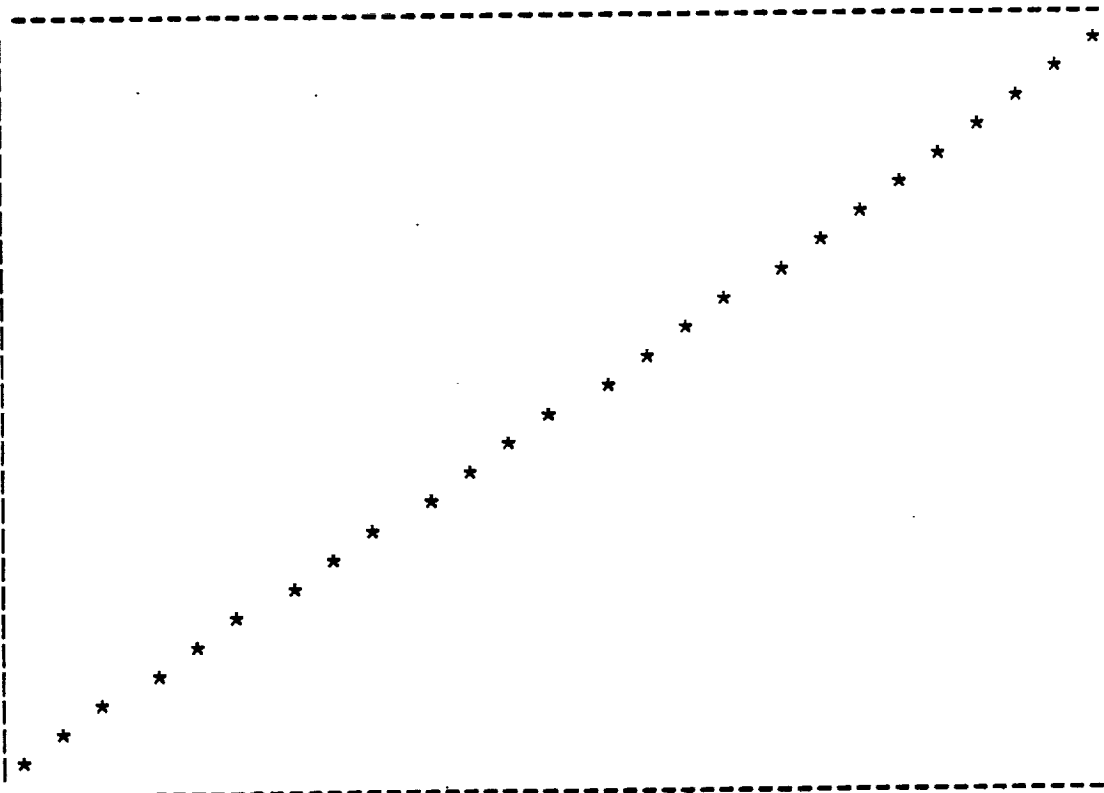
- 1) Body Temperature vs. Time
- 2) Heat Loss vs. Time
- 3) Body Weight vs. Time
- 4) Skin Temperature vs. Time

Please enter 1, 2, 3, or 4: >

3

The output file will be named BODYWT.TXT

X	Y
5.0	134.95
10.0	134.91
15.0	134.86
20.0	134.81
25.0	134.76
30.0	134.70
35.0	134.65
40.0	134.60
45.0	134.55
50.0	134.49
55.0	134.44
60.0	134.38
65.0	134.33
70.0	134.27
75.0	134.22
80.0	134.16
85.0	134.10
90.0	134.04
95.0	133.99
100.0	133.93
105.0	133.87
110.0	133.81
115.0	133.75
120.0	133.69
125.0	133.63
130.0	133.57



Where: X = TIME (min)      Y = BODY WEIGHT (lbs)

Would you like to plot some other data?

If YES, please enter Y; if NO, please enter N: >

Y

- 1) Body Temperature vs. Time
- 2) Heat Loss vs. Time
- 3) Body Weight vs. Time
- 4) Skin Temperature vs. Time

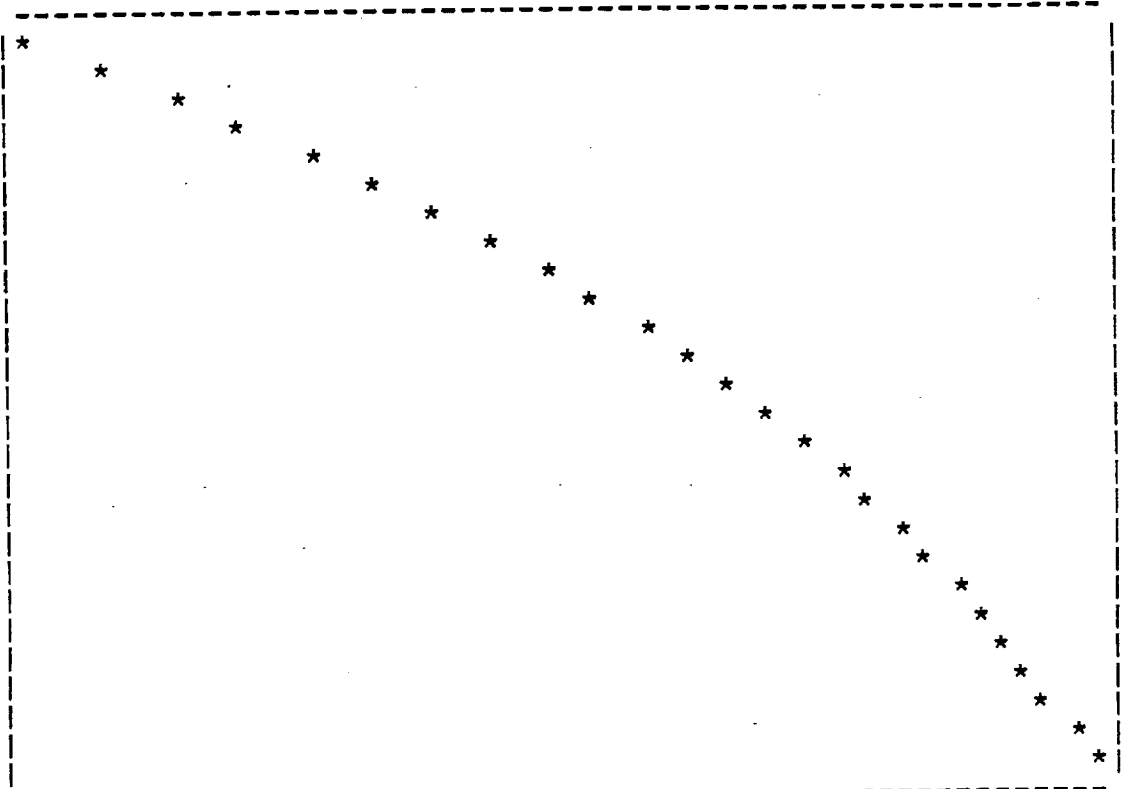
Please enter 1, 2, 3, or 4: >

4



The output file will be named SKINTEMP.TXT

X	Y
5.0	96.90
10.0	97.34
15.0	97.76
20.0	98.15
25.0	98.52
30.0	98.86
35.0	99.18
40.0	99.48
45.0	99.76
50.0	100.02
55.0	100.27
60.0	100.50
65.0	100.72
70.0	100.92
75.0	101.12
80.0	101.30
85.0	101.47
90.0	101.64
95.0	101.79
100.0	101.93
105.0	102.07
110.0	102.20
115.0	102.32
120.0	102.44
125.0	102.55
130.0	102.65



Where: X = TIME (min)      Y = SKIN TEMP. (Deg. F)

Would you like to plot some other data?

If YES, please enter Y; if NO, please enter N: >

n

Would you like to test some other conditions?

If YES, please enter Y; if NO, please enter N: >

n



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# APPENDIX 4

Chatterjee, Sharmista  
&  
Seagrave, Richard C.

Presented at

the 1993 International  
Conference on Environmental  
Science

July 1993

? An estimate of the second law thermodynamic  
efficiency of the various units comprising an  
environmental control & life support system (ECLS)

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## ABSTRACT

The objective of this paper is to present an estimate of the second law thermodynamic efficiency of the various units comprising an Environmental Control and Life Support Systems (ECLSS). The technique adopted here is based on an evaluation of the 'lost work' within each functional unit of the subsystem. Pertinent information for our analysis is obtained from a user interactive integrated model of an ECLSS. The model was developed using ASPEN. A potential benefit of this analysis is the identification of subsystems with high entropy generation as the most likely candidates for engineering improvements.

THIS WORK HAS been motivated by the fact that the design objective for a long term mission should be the evaluation of existing ECLSS technologies not only the basis of the quantity of work needed for or obtained from each subsystem but also on the quality of work.

In a previous study Brandhorst [1] showed that the power consumption for a partially closed and a completely closed regenerable life support systems were estimated as 3.5 kw/individual and 10-12 kw/individual respectively. With the increasing cost and scarcity of energy resources, our attention is drawn to evaluate the existing ECLSS technologies on the basis of their energy efficiency. In general the first law efficiency of a system is usually greater than 50%, [2]. From literature, the second law efficiency is usually about 10%, [3]. The estimation of second law efficiency of the system indicates the percentage of energy degraded as irreversibilities within the process. This estimate offers more room for improvement in the design of equipment.

From another perspective, our objective is to keep the total entropy production of a life support system as low as possible and still ensure a positive entropy gradient between the system and the surroundings. The reason for doing so is as the entropy production of the system increases, the entropy gradient between the system and the surrounding decreases, and the system

will gradually approach equilibrium with the surroundings until it reaches the point where the entropy gradient is zero. At this point no work can be extracted from the system. This is called as the 'dead state' of the system, [4].

## METHODS OF SECOND LAW ANALYSES :

The irreversibilities or entropy generation within a process is evaluated on the basis of the second law of thermodynamics using two widely used techniques. These are:

- Availability Analysis/Exergy Analysis
- Lost Work Analysis

Availability analysis or exergy analysis is a widely used technique. This was first proposed by Guoy and Stodola [5,6]. Availability is a measure of the useful work potential of a stream which is at a different state other than the environment. This concept has been extensively used in determining the efficiency in areas ranging from space heating to cryogenic processes, [7,8].

The method of Lost Work Analysis was first proposed by Seader [9].

For our study we chose the lost work approach as it provides a more intuitive feeling for the irreversibilities within a functional unit.

## CONCEPT OF LOST WORK ANALYSIS :

The basic requirement of the second law is :

The total entropy change of an isolated system,

$$\Delta S_{\text{sys}} \geq 0.0 \quad (1)$$

For a control volume with a steady state process where the surroundings are at a temperature of  $T_0$ , the rate of change of the total entropy of the system is given by, [10]

The rate of change of total entropy of the system = Net rate of entropy transfer by flowing streams + Rate of entropy exchange with the surroundings from heat transfer

Thus

$$\Delta(Sm)_{fs} - \frac{Q}{T_0} > 0.0 \quad (2)$$

where  $\Delta(Sm)_{fs}$  is the difference in entropy between the feed and the product  
 $Q$  is the net heat transfer from the system to the surroundings

For a steady state flow process there is no internal energy accumulation within the system. The law of conservation of energy can be expressed as ,

$$\Delta \left[ \left( H + \frac{1}{2} u^2 + zg \right) \right]_{fs} = Q - W_s \quad (3)$$

where  $\Delta \left[ \left( H + \frac{1}{2} u^2 + zg \right) \right]_{fs}$  is the difference in energy between the inflow and the outflow streams.  
 $Q$  is the heat flow into the system  
 $W_s$  is the work done by the system

For any system which requires work the amount of work required will be a minimum if the system undergoes a reversible change. This minimum work required is called the "ideal work", ( $W_{ideal}$ ). Since there is no degradation of work the entropy generation for a reversible process is equal to zero and equation (2) becomes

$$Q = T_0 \Delta(Sm)_{fs}$$

Substituting the above value in equation (3) and rearranging gives

$$W_{ideal} = T_0 \Delta(Sm)_{fs} - \Delta \left[ \left( H + \frac{1}{2} u^2 + zg \right) \right]_{fs} \quad (4)$$

In most processes the kinetic and potential energy terms are negligible, and equation (4) can be written as

$$W_{ideal} = T_0 \Delta(Sm)_{fs} - (\Delta H)_{fs} \quad (5)$$

It is justified to mention here that from an availability viewpoint, according to the definition of  $W_{ideal}$  as given in (5), the minimum work required is equivalent to the difference in availability between the input and the output streams.

For a work producing process the "lost work" is the work which is lost due to irreversibilities within the process. It is expressed as the difference between the

ideal work which could be produced by the process ( $W_{ideal}$ ) and the actual work produced by the process ( $W_s$ ). Thus from equations (3) and (5),  $W_{lost}$  can be written as

$$W_{lost} = T_0 \Delta(Sm)_{fs} - Q \quad (6)$$

Conventionally, there are two kinds of processes. A spontaneous process is one which produces work, i.e  $W_{ideal}$  is positive. Then

$$W_s = W_{ideal} - W_{lost} \quad (7)$$

A nonspontaneous process is one which requires some form of external work to be supplied, i.e  $W_{ideal}$  is negative. Hence

$$|W_s| = |W_{ideal}| + W_{lost} \quad (8)$$

Thereby the second law efficiency for each type of process can be defined as

$$\eta_2 \text{ (spontaneous process) } = \frac{W_s}{W_{ideal}} \quad (9)$$

$$\eta_2 \text{ (nonspontaneous process) } = \frac{W_{ideal}}{W_s} \quad (10)$$

#### METHODOLOGY ADOPTED :

The following steps were performed to evaluate the lost work and second law efficiency of each subsystem of an ECLSS based on the above developed concepts :

- Defining the subsystem boundary of the ECLSS subsystem chosen, i.e identifying the input and output streams from the subsystem chosen.
- Choosing the reference temperature. For our study we chose the space craft cabin temperature of 70°F.
- Evaluating the  $W_{lost}$  within each functional unit of the ECLSS subsystem.
- Depending on the subsystem information provided, we calculated the  $W_{ideal}$  for each subsystem.
- Knowing  $W_{lost}$  and  $W_{ideal}$ , the second law efficiency is thus evaluated.

It is to be noted that in order to calculate  $W_{lost}$  and  $W_{ideal}$ , detailed information about the input and output streams is required, i.e enthalpy, entropy and mass flow rate. To obtain the necessary data we developed a pseudo steady state model of the ECLSS using a state of the art chemical process simulator called ASPEN ( Advanced System for Process Engineering ). The underlying feature of our model is

that the inputs to the ECLSS subsystems are regulated by a user interactive model of the crew in the space craft. The crew model is appended to the main ASPEN code. The capability of the crew model is that given crew specifications of age, weight, gender and activity level, the model can be used to compute the flow rates of the different waste streams from the crew, which then serve as inputs to the ECLSS.

## RESULTS :

A conventional ECLSS consists of the following subunits [11] :

- Solid waste management
- Humidity condensate removal
- Trace removal subsystem
- CO<sub>2</sub> reduction subsystem
- CO<sub>2</sub> removal subsystem
- O<sub>2</sub> generation subsystem
- Water recovery subsystem

Presented herein are the results obtained for a few sample technologies which are commonly in use in an ECLSS design.

## WET OXIDATION OF SOLID WASTE :

The solid waste is oxidized in an autoclave at a pressure of 1067 psia in the presence of water,[12]. The reaction temperature depends on the carbon content of the feed and is usually between 100 and 374 °C. For our modeling purposes we assume that only the carbon content of the feed is oxidized.

For the ASPEN model the reactor is modeled using a RSTOIC block as shown in Figure 1. The reactor temperature is set according to the carbon content of the feed using the linear relationship as given by Takahashi [12]

$$\% \text{ of carbon in feed} = -0.65 \times \text{oxidation temperature} + 194 \quad (11)$$

The mass and energy balance information of the streams involved in the process is shown in Table 1. It is to be noted that all these values are for a basal case of a crew consisting of 1 man of age 25 years weighing 60 kg resting at basal metabolic rate.

Table 1: Properties of streams involved in wet oxidation process

Stream	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr°R)
S1	$3.44 \times 10^{-4}$	$12.91 \times 10^{-4}$	$23.56 \times 10^{-7}$
S2	$9.16 \times 10^{-4}$	$-1.4 \times 10^{-3}$	$-2.64 \times 10^{-3}$
S3	$1.26 \times 10^{-3}$	-4.77	$-3.63 \times 10^{-6}$
S4	$1.26 \times 10^{-3}$	-4.85	$1.72 \times 10^{-5}$
S5	0	0	0
Q1	Heat duty = -4.77 Btu/hr		
Q2	Heat duty = -0.08 Btu/hr		

The lost work analysis of each unit operation block comprising the Solid waste oxidizer is given in Table 2.

Table 2: Lost Work estimation of the Solid Waste Oxidizer

Unit operation block	Lost Work (Btu/hr)	% of total lost work
Wet oxidizer	4.71	98.1
Depressurizer	0.091	1.9
Total lost work	4.801	

$$\begin{aligned} W_{\text{ideal}} &= 530 (1.72 \times 10^{-5} + 26.36 \times 10^{-7} - 23.56 \times 10^{-7}) - (-4.85 - 12.91 \times 10^{-4} + 14.05 \times 10^{-4}) \\ &= 4.86 \quad \text{Btu/hr} \end{aligned}$$

$W_{\text{ideal}}$  being positive, this is a spontaneous process. Hence

$$\begin{aligned} \eta_2 &= \frac{0.059}{4.86} \\ &= 1.21 \% \end{aligned}$$

The lost work analysis of each unit operation block, comprising the Catalytic Oxidizer is shown in Table 4.

## CATALYTIC OXIDATION OF CONTAMINANT GASES :

The Catalytic oxidation process is chosen for trace contaminant removal. This design was proposed by Ammann, [13]. In this subsystem, the incoming trace gas is split into two fractions depending on its methane content (i.e higher the methane content, the greater the volume of gas which goes into the high temperature oxidizer). One portion of the incoming trace gas is oxidized in a high temperature catalytic oxidizer (HTCO) which is maintained at a temperature of 400 - 450 °C. Prior to entering the HTCO the gas is heated in an electric heater. Remaining portion of the gas is oxidized in a low temperature catalytic oxidizer (LTCO) which is maintained at ambient temperature of 70 °F. ASPEN model of this subsystem is shown in Figure 2.

ASPEN results for this model is shown in Table 3.

Table 3: Stream properties of Catalytic oxidation subsystem

Stream	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr °R)
S1	35.66	- 3291.38	1.17
S2	3.45	- 318.44	0.113
S3	3.45	135.9	0.71
S4	3.45	309.64	0.86
S5	3.45	309.33	0.86
S6	3.45	-145.0	0.39
S7	32.21	-2972.98	1.05
S8	32.21	-2975.56	1.05
S9	35.66	-3120.25	1.49
Q1 Heat duty :	173.7	(Btu/hr)	
Q2 Heat duty :	- 0.297	(Btu/hr)	
Q3 Heat duty :	- 2.56	(Btu/hr)	

Table 4: Lost Work estimation of Catalytic Oxidizer System

Unit operation block	Lost Work (Btu/hr)	% of total lost work
Diverter	0	0
Heat Exchanger	67.31	38.2
Heater	79.5	45.1
HTCO	0.297	0.17
LTCO	2.56	1.45
Mixer	26.5	15.04
Total lost work	176.17	

$$W_{ideal} = 530 (1.49 - 1.17) - (-3120.25 + 3291.38)$$

$$= -1.53 \text{ Btu/hr}$$

This is a nonspontaneous process. Hence

$$W_s = 1.53 + 176.17$$

$$= 177.7 \text{ Btu/hr}$$

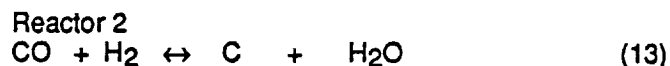
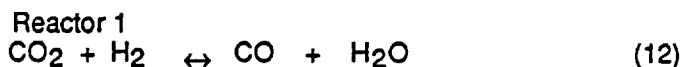
$$\eta_2 = \frac{1.53}{177.7}$$

$$= 0.86\%$$

## BOSCH SUBSYSTEM :



The Bosch subsystem was chosen for CO<sub>2</sub> reduction. The design for our model is based on a design proposed by Minemoto et al, [14]. A series of two reactors are used. The first reactor is at a temperature of 1300 [K] while the other reactor is operating at a temperature of 900 [K]. The reactions are given by :



Since all the CO<sub>2</sub> is eventually converted to C a stoichiometric ratio of H<sub>2</sub> to CO<sub>2</sub> is maintained.

The properties of the streams present in the Bosch subsystem as obtained from our model is shown in Table 5.

Table 5: Stream properties of Bosch subsystem

Stream	mass flow rate (lb/hr)	total enthalpy (Btu/hr)	total entropy (Btu/hr °R)
S1	0.048	-183.79	-6.04×10 <sup>-4</sup>
S2	4.37×10 <sup>-3</sup>	-54.16×10 <sup>-6</sup>	-5.98×10 <sup>-7</sup>
S3	0.398	-677.1	- 0.139
S4	0.398	515.04	0.778
S5 solid	1.3×10 <sup>-2</sup>	4.51	4.27×10 <sup>-3</sup>
S5 vapor	0.385	-130.4	0.436
S6	3.9×10 <sup>-2</sup>	- 268.11	- 0.087
S7 solid	1.3×10 <sup>-2</sup>	-0.08	-1.5×10 <sup>-4</sup>
S7 vapor	0.346	-507.11	-0.177
S8	1.3×10 <sup>-2</sup>	-0.015	-2.87×10 <sup>-5</sup>
S9	0.398	- 677.1	-0.139
Q1	Heat duty:	1192.14	Btu/hr
Q2	Heat duty:	-640.93	Btu/hr
Q3	Heat duty:	-649.41	Btu/hr

Table 6 indicates the amount of lost work in each functional unit comprising the Bosch subsystem.

Table 6: Lost work analysis of unit operation blocks of Bosch subsystem

Unit operation block	Lost work (Btu/hr)	%lost work
Mixer	6.89	0.55
Reactor 1	486.01	39.04
Reactor 2	461.95	37.11
Condensate Remover	276.13	22.18
Solid carbon remover	13.78	1.11
Total lost work	1244.76	

$$\begin{aligned} W_{\text{ideal}} &= 530 (-2.87 \times 10^{-5} - 0.087 + 6.21 \times 10^{-4} \\ &\quad + 5.98 \times 10^{-7} - 1.72 \times 10^{-5}) - \\ &\quad (-286.11 - 0.015 + 178.94 + \\ &\quad 54.16 \times 10^{-6} + 4.85) \end{aligned}$$

$$= 38.53 \quad \text{Btu/hr}$$

Hence this is a spontaneous process.

$$\begin{aligned} W_s &= 38.53 - 1244.76 \\ &= -1206.23 \end{aligned}$$

This is an example of a highly nonideal process. The actual process is spontaneous however under simulated working conditions the process requires external work to be supplied.

#### STATIC FEED WATER ELECTROLYSIS :

This technique is used for O<sub>2</sub> generation. Our model is based on a design proposed by Fortunato et al [15]. In this method the water from the water

regeneration system is electrolyzed in a water retention matrix to produce H<sub>2</sub> and O<sub>2</sub>. The electrolysis chamber is maintained at 30psia. The ASPEN model for the process is shown in Figure 4. The water from the water regeneration unit is pressurized to 30 psia before being fed into the electrolysis chamber. A cooler is used prior to the electrolysis chamber to remove the heat generated due to compression of water. The compressed water is cooled to ambient temperature before being fed into the electrolysis cell. Since there are no tailor made blocks to simulate the reactions occurring at the electrodes in ASPEN, the reaction was simulated using a RSTOIC block.

Table 7: Properties of streams present in the Water Electrolysis subsystem

Stream	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr °R)
S1	$9.6 \times 10^{-2}$	-654.8	-0.21
S2	$9.6 \times 10^{-2}$	-654.83	-0.21
S3	$9.6 \times 10^{-2}$	-654.86	-0.21
S4	$9.6 \times 10^{-2}$	-0.38	-0.27
S5	$1.07 \times 10^{-2}$	-0.25	$-4.76 \times 10^{-4}$
S6	$8.52 \times 10^{-2}$	-0.13	$-2.46 \times 10^{-4}$
Q1	Heat duty: -0.03	Btu/hr	
Q2	Heat duty: 654.55	Btu/hr	

Table 8 presents an analysis of the lost work within each subsystem.

Table 8: Lost work analysis within the Water Electrolysis subsystem

Unit operation block	Lost work (Btu/hr)	%lost work
Pump	0.427	0.38
Cooler	0.03	0.03
Electrolyzer	96.99	87.08
Gas separator	13.93	12.51
Total lost work	113.38	

$$\begin{aligned}
 W_{ideal} &= 530 (-4.76 \times 10^{-4} - 2.46 \times 10^{-4} + 0.21) \\
 &\quad - (-0.13 - 0.25 + 654.8) \\
 &= -543.5 \text{ Btu/hr}
 \end{aligned}$$

Thus this is an example of a nonspontaneous process.

$$W_s = -656.88 \text{ Btu/hr}$$

$$\begin{aligned}
 \eta_2 &= \frac{543.5}{656.88} \\
 &= 82.74\%
 \end{aligned}$$

#### HUMIDITY CONDENSATE SEPARATOR :

In order to maintain the cabin humidity at a desired level, the exit air from the trace removal subsystem is cooled to a temperature such that the amount of moisture in the air leaving the condenser separator is equal to the amount of moisture desired in the cabin. The condensate is removed and treated to obtain water of potable quality. For the ASPEN model the condenser separator is modeled as a single unit using a SEP block. The temperature of the condenser is set in a user incorporated Fortran subroutine which takes into account the humidity levels of the incoming and outgoing streams.

Table 9: Stream properties of streams occurring in Humidity Condense Separator

Stream	Mass flow rate (lb/hr)	Total enthalpy (Btu/hr)	Total entropy (Btu/hr °R)
S1	35.66	- 3120.22	1.49
S2	$7.18 \times 10^{-2}$	- 489.58	- 0.154
S3	35.59	- 2783.35	1.35
Q1	Heat duty:	- 152.71 Btu/hr	

Since the heat of condensation is not being used to do any useful work, hence

$$\begin{aligned} \text{Lost work} &= 530 (1.35 + 0.154 - 1.49) + 152.71 \\ &= 160.13 \quad \text{Btu/hr} \end{aligned}$$

$$\begin{aligned} \text{Wideal} &= 530 (1.35 + 0.154 - 1.49) \\ &\quad - (-489.58 - 2783.35 + 3120.22) \\ &= 160.13 \quad \text{Btu/hr} \end{aligned}$$

This is a spontaneous process.

$$W_s = 0$$

$$\text{Thus } \eta_2 = 0$$

This is valid since we had assumed that the heat of condensation is not used for doing useful work, thereby the amount of work which can be obtained from the process is zero.

## CONCLUSIONS :

As shown in Tables 2, 4 and 6 lost work analysis provides a means of identifying areas within a subsystem where maximum work is lost due to irreversibilities. The magnitude of second law efficiency of some subsystems like the Catalytic Oxidation process or the Bosch subsystem reveal that these subsystems merit considerable attention to redesign their functional units from an energy conservation viewpoint.

For example, our study shows that percentage of lost work in the reactors used for CO<sub>2</sub> reduction is between 35 to 39 %. It is hopeful that this will provide

some insight to the design scientists to redefine the operating conditions so as to optimize between yield of desired product and lost work.

The overall conclusion to be drawn from this paper is that there exists a potential for energy conservation in the currently used ECLSS technologies which warrants evaluation of the present operating conditions.

## REFERENCES :

- [1] Brandhorst, Jr., H., W., "Energy Requirement for the Space Frontier," Paper No. 912064, Twenty first Intersociety Conference on Environmental Systems, San Francisco, 1991.
- [2] Cook, E., Sci. Am, 225, 83, 1971.
- [3] Reistad, G., M., Trans ASME J., Engng Power, 97, 429, 1975.
- [4] Keenan, J., H., Mech Engng, 54, 195, 1932.
- [5] Guoy, G., J. physique, 8, 501, 1889.
- [6] Stodola, A., Zeitschrift, VDI, 32, 1086, 1898.
- [7] Herbert, W., H., and Stephen, C., H., "Second Law Analysis : An Alternative Indicator of System Efficiency", Energy, 5, 865 - 874, 1980.
- [8] Ahern, J. E., "Applications of the Second Law of Thermodynamics to Cryogenics - A Review", Energy, 5, 891 - 898, 1980.
- [9] Nevers, N. D., Seader, J. D., "Lost Work. A Measure of Thermodynamic Efficiency", Energy, 5, 757 - 769, 1980.
- [10] Smith, J., M., and Van Ness, H., C., Introduction to Chemical Engineering Thermodynamics, Mc Graw- Hill Book Company, 4th edition, 548 - 564. 1987.
- [11] Rohatgi, N., et al., "Human Life Support During Interplanetary Travel and Domicile, Part - 2 : Generic Modular Flow Schematic Modeling", Paper No. 911332, Twentyfirst Intersociety Conference on Environmental Systems, San Francisco, 1991.
- [12] Takahashi, Y., Ohya, H., "Wet-Oxidation Waste Management System for CELSS", Paper No. 851398, Fifteenth Intersociety Conference on Environmental Systems, Portland, 1985.
- [13] Ammann, K., "Development of the Catalytic Oxidizer Technology for the European Space Program", Paper

No. 891539, Nineteenth Intersociety Conference on Environmental Systems, San Diego, 1989.

- 4] Minemoto, M., et al., " Study of Air Revitalization System for Space Station", Paper No. 891576, Nineteenth Intersociety Conference on Environmental Systems, San Diego, 1989.
- 5] Fortunato, F., A., et al., " Static Feed Water Electrolysis System for Space Station Oxygen and Hydrogen Generation", Paper No. 880994, Eighteenth Intersociety Conference on Environmental Systems, San Francisco, 1988.

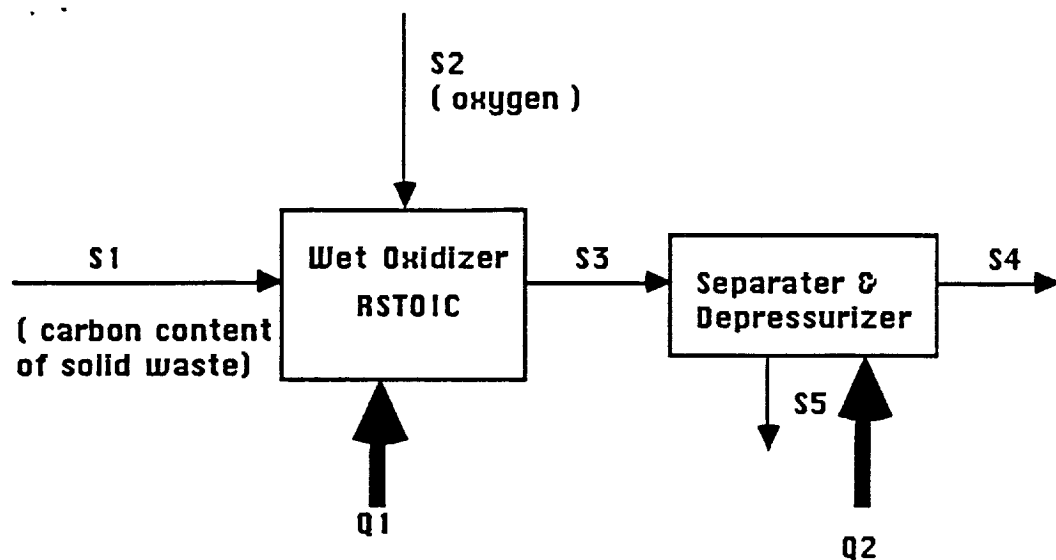


Figure 1: Schematic of Solid Waste Wet Oxidation Subsystem.

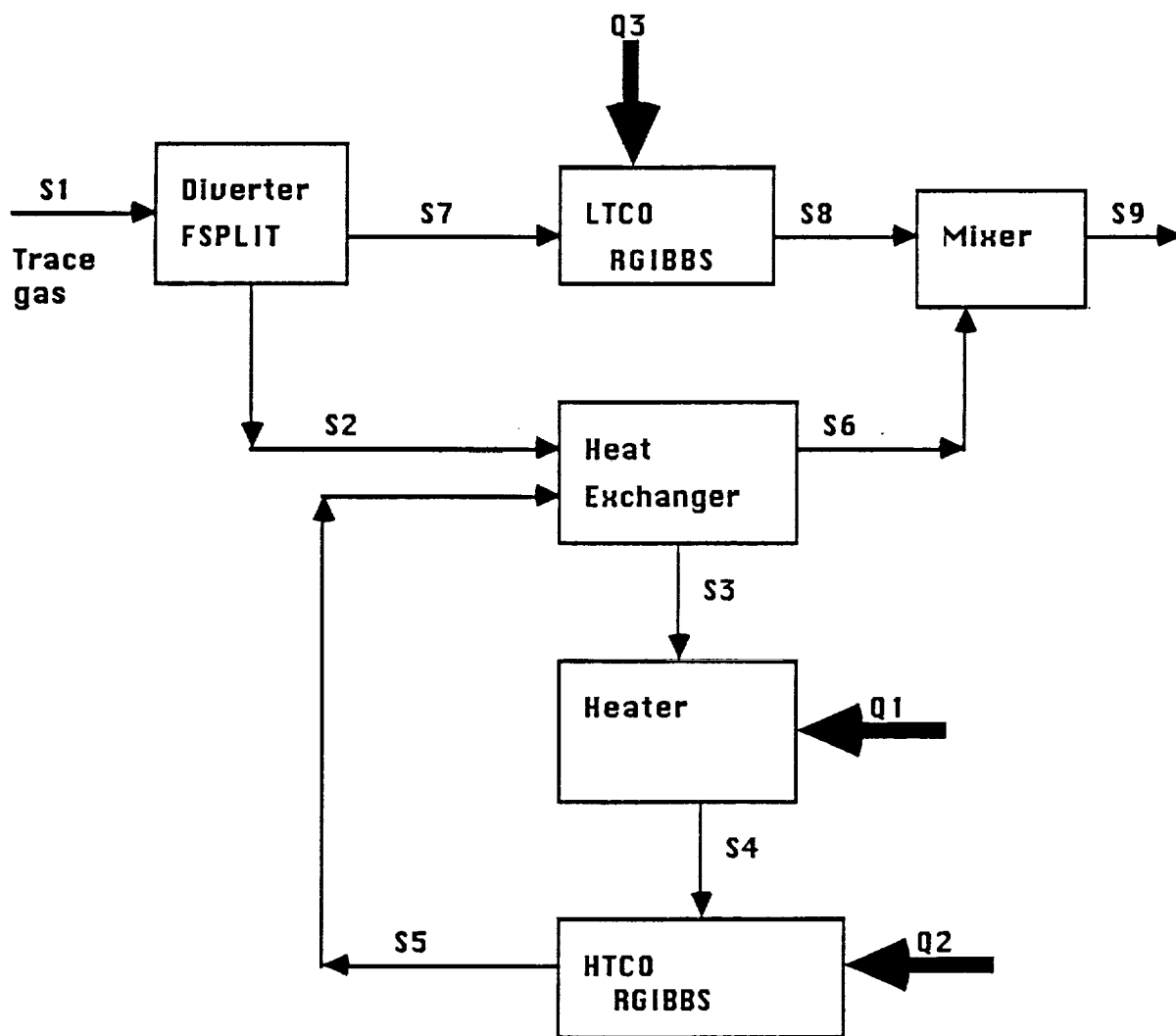


Figure 2: Schematic of Catalytic Oxidation Process

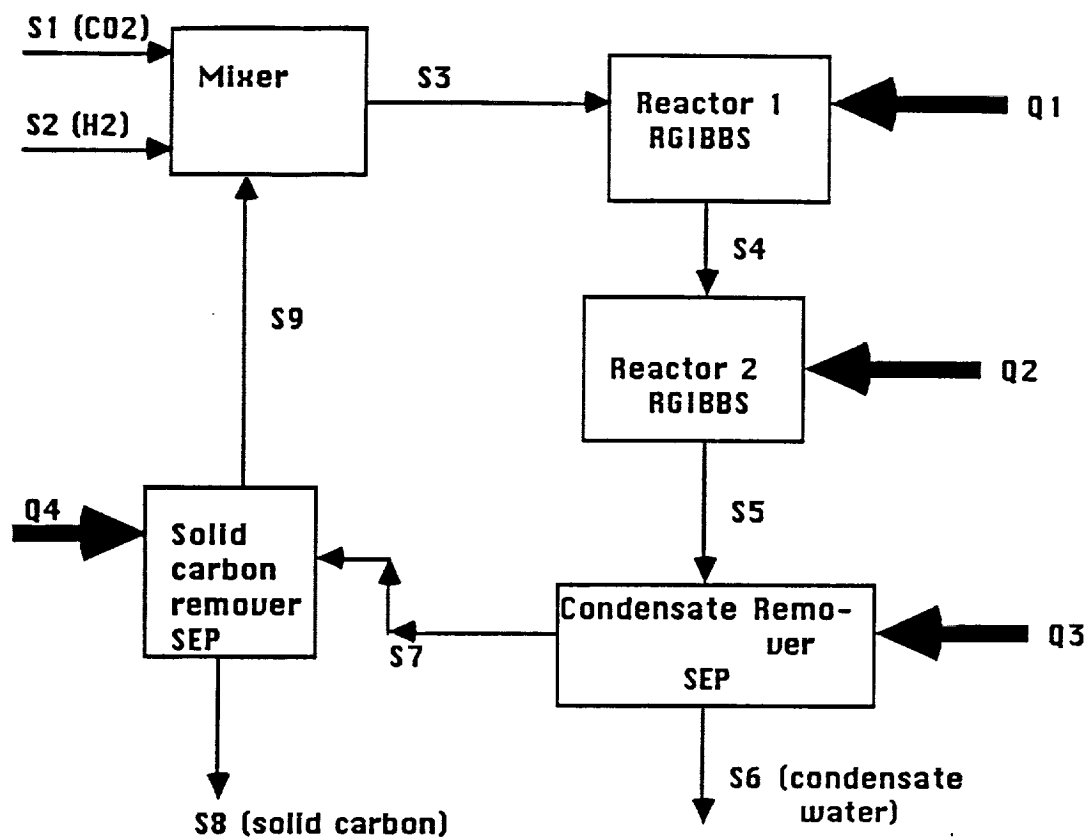


Figure 3: Schematic of Bosch subsystem

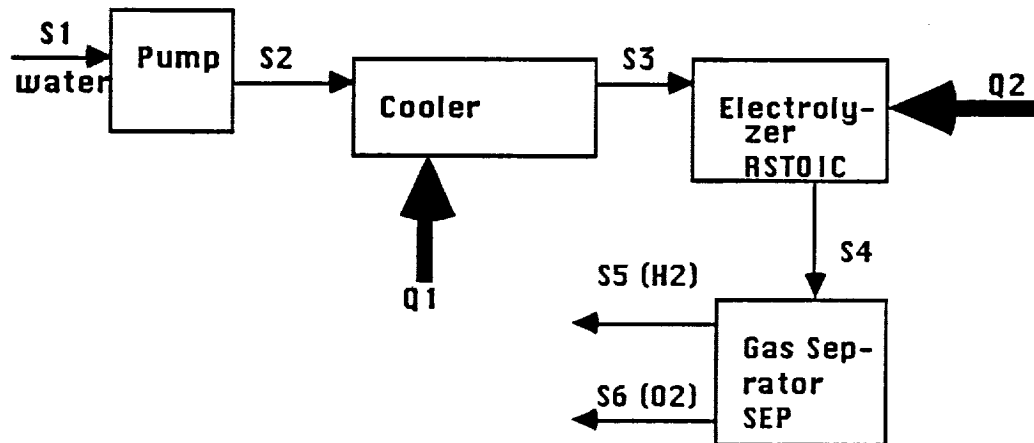


Figure 4: Schematic of Water Electrolysis process

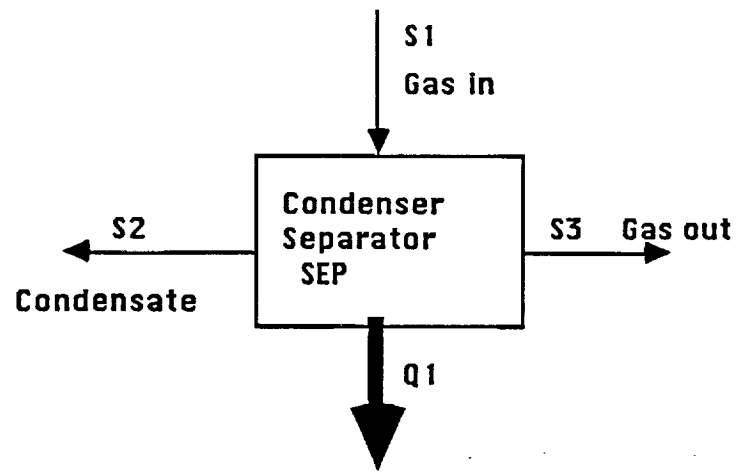


Figure 5: Schematic of Humidity Condensate Separator

